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HUGHES
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ELECTRON DYNAMICS DIVISION

FINAL TECHNICAL REPORT

PHASE B

(NASA-CR-189254) INVESTIGATION OF MICRO-GRAVITY EFFECTS ON HEAT PIPE THERMAL PERFORMANCE AND WORKING FLUID BEHAVIOR, PHASE B Final Technical Report (Hughes Aircraft Co.) 105 p CSCL 22A G3/29

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INVESTIGATION OF MICRO-GRAVITY EFFECTS ON HEAT PIPE THERMAL PERFORMANCE AND WORKING FLUID BEHAVIOR

PREPARED FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
GREENBELT, MD 20771

NAS5-30359

CONTRACT NO. NAS5-30359

NASA CONTRACTOR REPORT
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JANUARY 1990

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PREFACE

The Phase B study documented in this report was intended to develop the design of the experiment in sufficient detail to provide information to permit the Technical Officer to ascertain, with a high level of confidence, the feasibility of the experiment. This activity also defined the cost of building, testing and integrating the experiment and the time phasing and schedule needed to complete the experiment. Labor requirements, in terms of heads (hours per month), schedule, and material requirements for Phase C/D are summarized in the Appendix to this report. However, the proposed rates and costs are included under separate cover.

This study was conducted under NASA Goddard Space Flight Center Contract NAS5-30359 under the direction of R. McIntosh who is the Technical Officer for this program.

The study was performed at Hughes Aircraft Company with G. L. Fleischman as the Program Manager and A. Basiulis as Senior Technical and Management Adviser. K. D. Gier was Principal Investigator for the thermal performance experiment. M. O. Smith, of Hughes Space and Communications Group, El Segundo, CA, was the Deputy Program Manager and Principal Investigator for the nutation divergence experiment.

We would like to give special acknowledgment to R. N. Stuckey of the NASA Johnson Space Center, Spacelab and Middeck Integration Department, who was selected as our Payload Integration Manager during Phase B. He fabricated a mockup of the nutation divergence experiment, and obtained an opportunity to fly it on the NASA KC-135 free-fall training aircraft. He was able to check-out spin-up and handling techniques on this flight.

D. Butler of NASA Goddard supported the Pre-Phase 0 Safety effort, and some of his comments are included in Section 8.0 of this report.

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1.0 INTRODUCTION

The purpose of this experiment is to develop an in-depth understanding of the behavior of heat pipes in space. Both fixed conductance heat pipes (FCHPs) with axial grooves and variable conductance heat pipes (VCHPs) with porous wicks will be investigated. This understanding will be applied to the development of improved performance heat pipes subjected to various accelerations in space, including those encountered on a lunar base or Mars mission. More efficient, reliable, and lighter weight spacecraft thermal control systems should result from these investigations.

There is an increased need to integrate heat pipes into thermal control systems for space applications: In commercial and military satellites due to increased payload and temperature control requirements which demand efficient waste heat rejection; in space platforms due to large scale structure requirements which demand long heat transport distances; in proposed future lunar and Mars bases due to stringent power conservation requirements which demand passive thermal management systems.

Experiments are needed,however, because a problem often arises in how to use heat pipe ground test data to make performance predictions in space. During ground testing, gravity dominates the capillary forces and becomes a limiting factor, whereas surface tension forces dominate in a micro-gravity environment. Moreover, both thermal performance and vehicle stabilization are affected by liquid sloshing caused by spacecraft accelerations due to motions in orbit. These motions may result from rendezvous and docking, changing orbits, or threat avoidance including space debris as well as military threats. A heat pipe may also be exposed to a variety of fractional gravity accelerations related to space vehicle spinning for stabilization or surveillance purposes. Satellites are often spin-stabilized during transfer orbit and then despun after orbit insertion.

Another problem is the uncertainty of predicting microgravity performance in the presence of excess fluid. During space operation, a heat pipe may require excess fluid to compensate for fluid contraction at low temperature operation. During ground testing, however, gravity causes the fluid excess to puddle creating an unpredictable (and erroneous) enhancement to heat pipe performance.

Heat pipes on spacecraft subject to acceleration, including spacecraft that are spin-stabilized in transfer orbit, and those which experience high or sustained acceleration parallel to the heat pipe axis pose another area of concern. In such cases, the heat pipe working fluid may accumulate at one end of the heat pipe. After the accelerating forces cease, the heat pipe will not function until the capillary wicking action redistributes the working fluid throughout the wicking system. Currently, too little is known to accurately predict the rewicking time from

ground testing, because the capillary forces responsible for the wicking action are much weaker than the gravitational force.

Nutation growth is an area of concern in the design of spinning spacecraft, especially for vehicles which spin in transfer orbit. Onboard passive energy dissipation is then destabilizing and often requires active measures to ensure adequate stability. Both the divergence of nutation and its attenuation by the attitude control system are roughly exponential and hence may be characterized by exponential time constants.

In summary, there are numerous heat pipe applications for NASA, commercial, and military spacecraft. All typically use a design margin on the order of 100 percent. Moreover, system performance data obtained from flight tests to date is insufficient to correlate models or to determine the amount of overdesign necessary.

2.0 EXPERIMENT BACKGROUND AND OBJECTIVES

2.1 BACKGROUND ISSUES

Because of the increased need for heat pipe technology for space systems, it is becoming increasingly apparent that there is a need to accurately predict the micro-gravity performance characteristics of a given heat pipe design. Space heat pipe thermal performance is currently predicted by two methods:

- Analytical Models; e.g., NASA Groove Analysis Program (GAP)*.
- Extrapolation of tilt test data to zero tilt.

Figures 1 and 2 show a comparison between typical axial groove heat pipe test results and the analytical predictions. The prediction in Figure 1 was made using the NASA Groove Analysis Program (GAP), referred to above, and the predictions in Figure 2 were made using a model developed at Hughes. In both cases it can be seen that the models over-predict the performance at low tilts, by a substantial margin, and under-predict at higher tilts. The test data may have been influenced by gravitational effects, but spacecraft systems engineers prefer to use the most conservative approach because the analytical models have not been verified in space.

Most heat pipe flight experiments to date have demonstrated feasibility only. Heat pipe performance limits in a micro-gravity environment are needed. Specifically, we plan to obtain quantitative thermal performance data for axial groove and porous wick heat pipes subjected to various accelerations between 0 and 1-g in a micro-gravity environment.

Nutation divergence tests are also necessary to determine the time constants for axial groove and porous wick heat pipes in a micro-gravity environment. Results will be applied to the analytical modeling of nutation induced by the motion of heat pipe working fluid, permitting design improvements which minimize the interference of heat pipes with spacecraft dynamics.

2.2 OBJECTIVES

The Hughes heat pipe performance experiment is designed to meet the following objectives:

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* Jen, Nsianmin F. and Kroliczek, E. J., "User's Manual for Groove Analysis Program (GAP)", B & K Engineering, Inc., NASA Goddard Contract No. NAS5-22563, 1976.

** Salvatore, J. O. and Porter, W. W., "ATS-V Heat Pipe Tests and Dimensional Analysis," Hughes Aircraft Company, NASA Goddard Contract No. NAS5-21554, 1970.

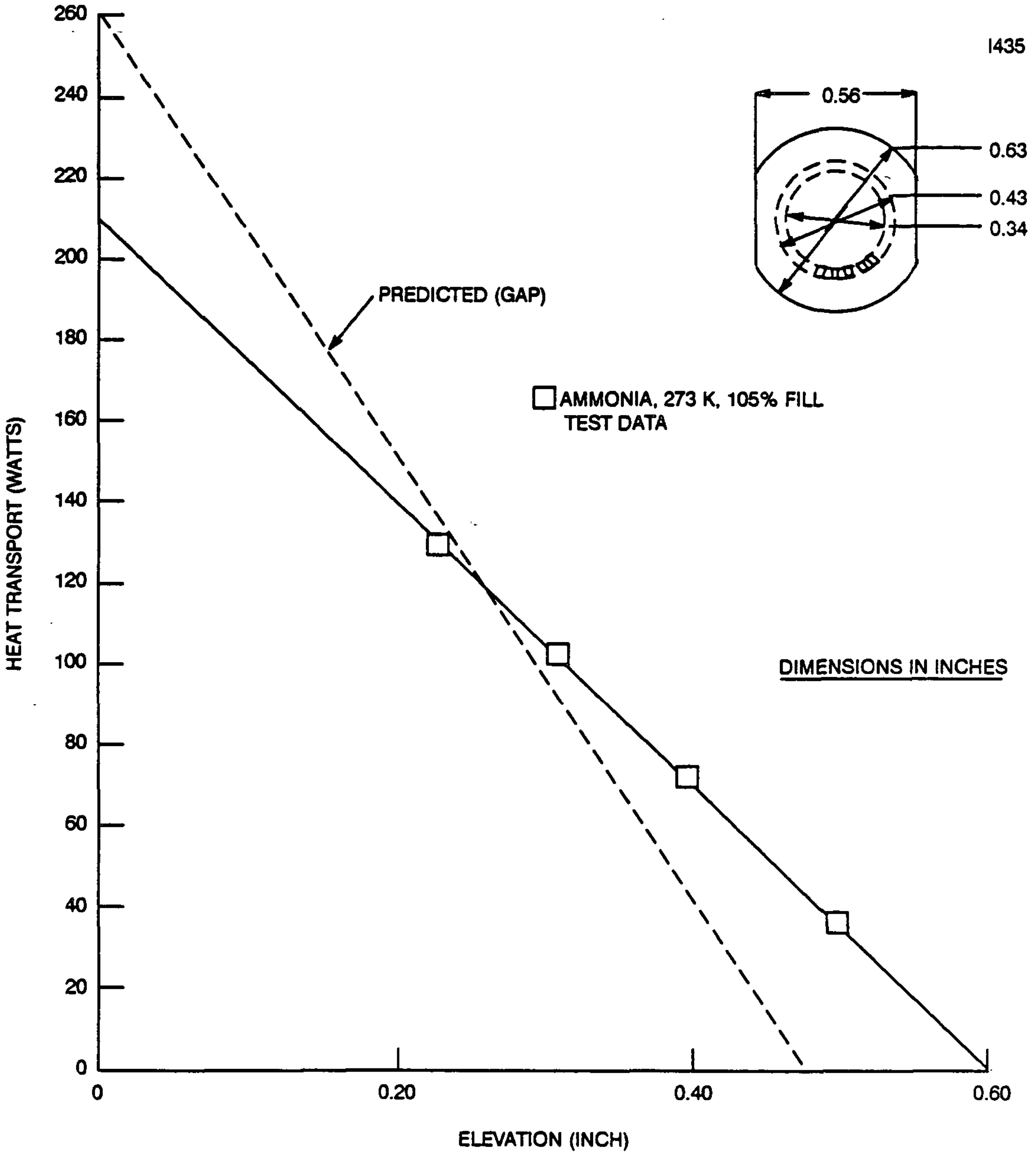

Figure 1 Performance comparison between predictions and test data for an axial groove heat pipe (Ref. AIAA 77-747).

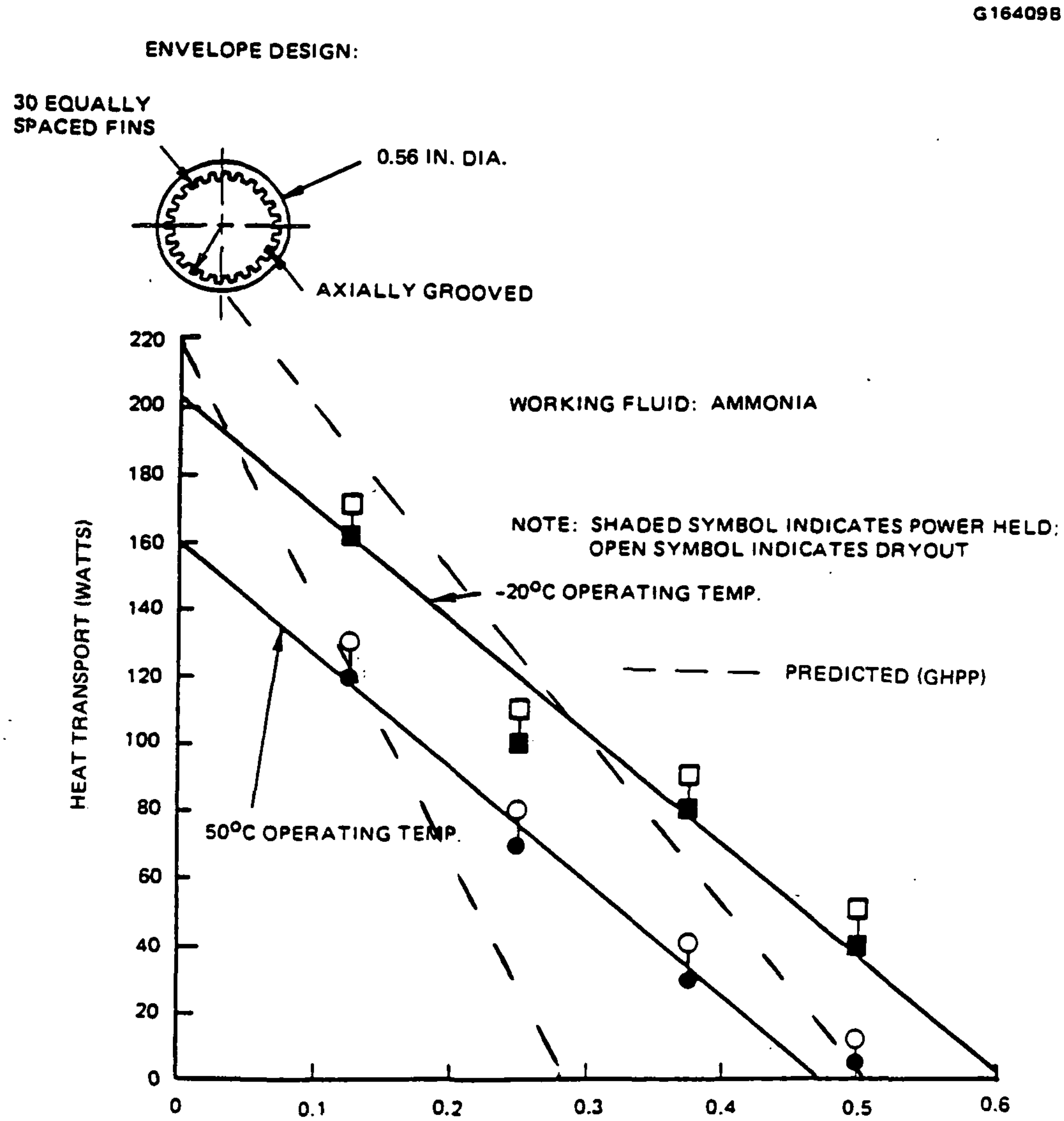

Figure 2 Performance comparison between predictions and test data for Hughes axial groove heat pipe.

2.2.1 Thermal Performance Objectives

1) Obtain a 0 to 1-g verification of existing analytical models (e.g., GAP, WICKPER) for thermal transport performance and fluid management of axially grooved and porous wick heat pipes. Both fixed conductance and variable conductance heat pipes will be evaluated.

2) Compare micro-gravity and ground test data to establish design margins for axially grooved and porous wick heat pipes.

3) Obtain quantitative data on start-up and rewicking in micro-gravity.

4) Update analytical models based on spinning ground test and flight performance.

Recovery rates for deprimed wicks as well as the effect of fluid charge will be determined. These results will be compared with analytical models, ground test data, and existing flight data. Note that the results of (1) and (2) will permit applications with less design margin and allow the use of fewer or smaller heat pipes with the accompanying weight savings.

2.2.2 Nutation Divergence Objectives

1) Perform tests to determine nutation divergence time constants for fixed conductance and variable conductance heat pipes.

2) Develop analytical model and upgrade on the basis of flight data.

Effects of fluid charge, spin rate, and center-of-gravity (cg) location on damping will be determined.

3.0 **APPROACH**

As discussed in the preceding sections, both thermal performance and nutation divergence (fluid sloshing) type experiments will be performed. To minimize complexity and cost, as well as to improve manifesting flexibility, these experiments are planned for the middeck area of the crew compartment. An overriding theme of our experiment is to "keep it simple".

3.1 TEST ARTICLES

Two configurations of monel heat pipes containing triply distilled water as the working fluid were selected for the experiment: fixed conductance heat pipes (FCHPs) with grooved internal walls as shown in Figure 3, and variable conductance heat pipes (VCHPs) with internal copper mesh wicks and noncondensable gas reservoirs as shown in Figure 4. Note, however, that the heat pipes will <u>not</u> have noncondensable gas inside them for this series of experiments. This will allow us to more clearly observe temperature gradients in the heat pipe wall caused by the presence of excess liquid.

Both configurations represent current heat pipe technology and hence provide an appropriate basis for testing. The axial groove heat pipe is the most common design specified for communications, surveillance, scientific, and other spacecraft. The porous wick design is being used on current spacecraft designs, and is being proposed for future missions.

3.2 EXPERIMENTS IDENTIFIED

Program objectives are accomplished by selecting two categories of experiments--heat pipe thermal performance and nutation divergence--as outlined below:

- Thermal Performance
    - Heat transport capacity and surface temperature distributions for heat pipes subjected to various acceleration levels from 0 to 1-g.
    - Recovery rates for deprimed heat pipe wicks.
    - Effect of excess liquid on heat pipe thermal performance.
- Nutation Divergence
    - Time constants for accelerations induced by liquid in circumferential heat pipes.

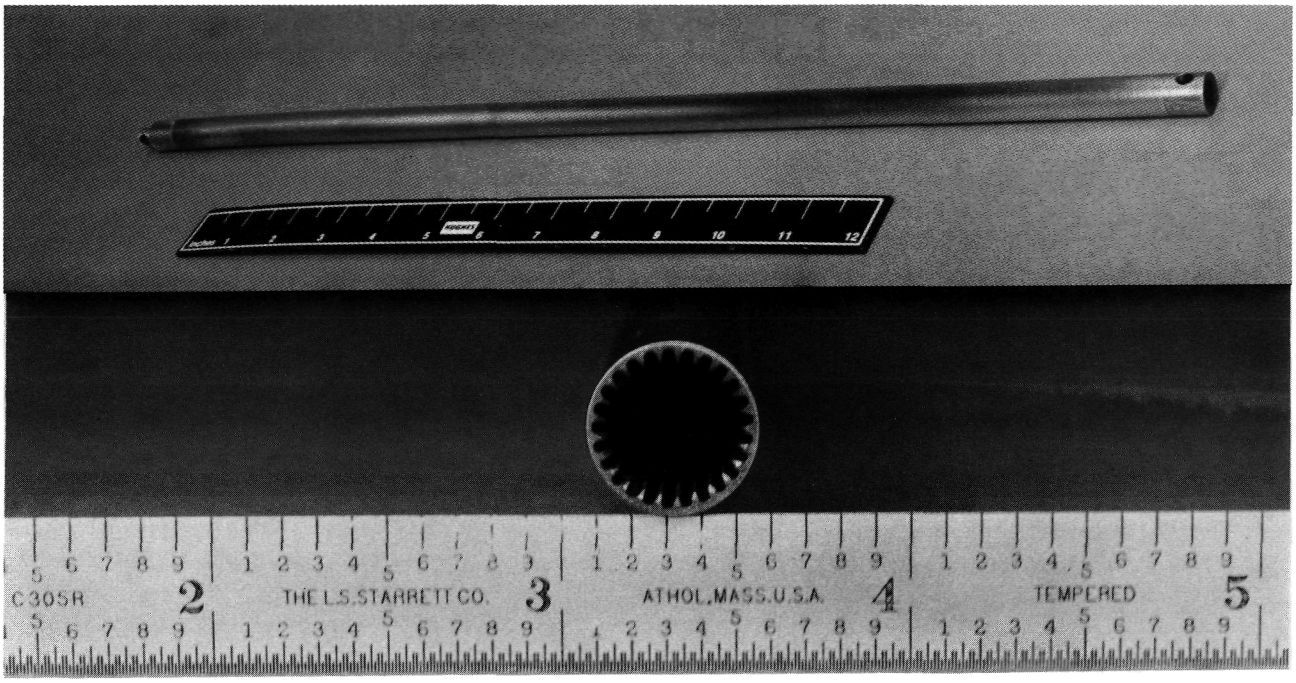

Figure 3 Axial grooved constant conductance heat pipe.

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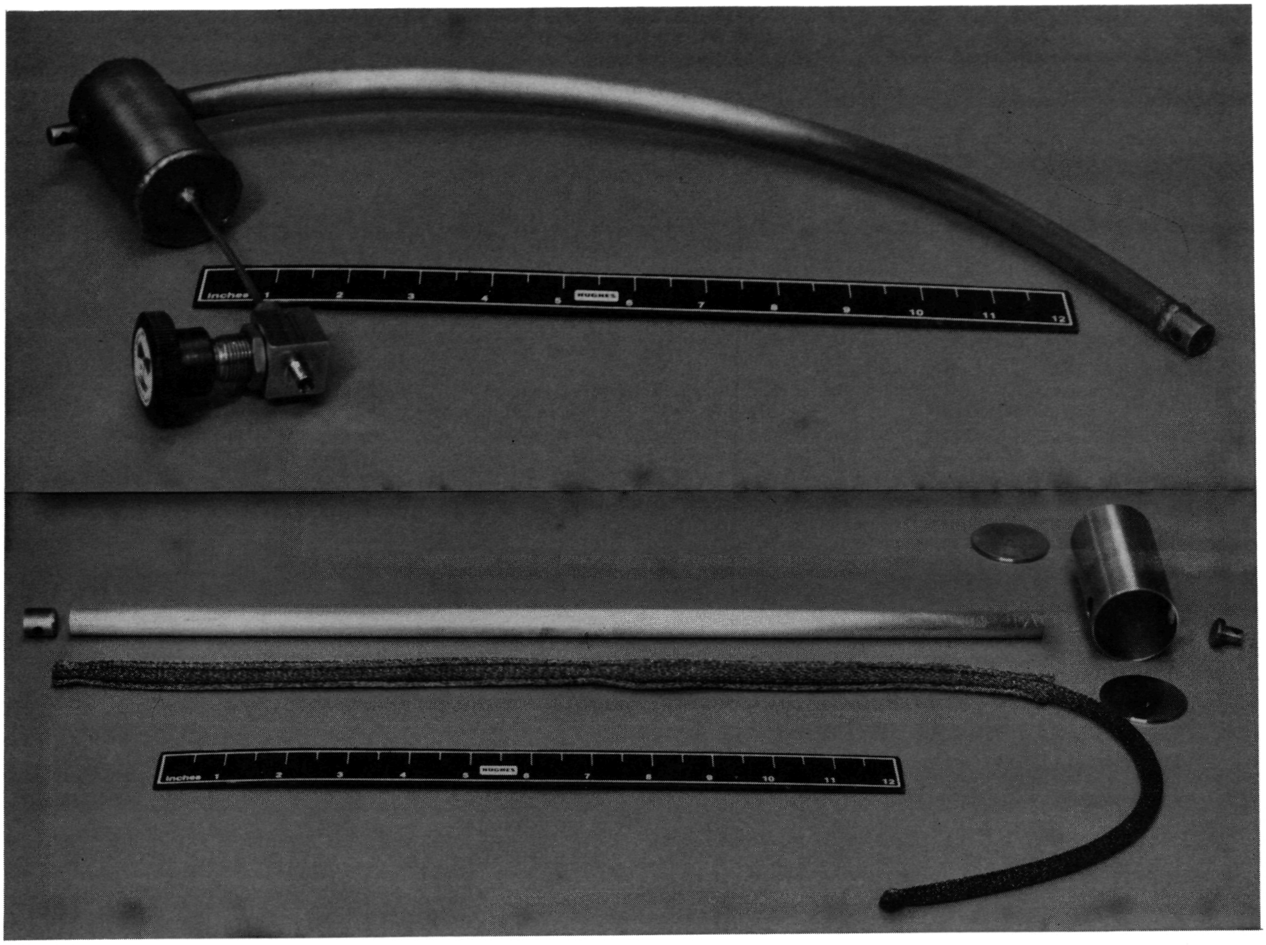

Figure 4 Variable conductance heat pipe with central core wick.

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Thermal performance tests will examine heat transport capacity and surface temperature distributions for fixed conductance heat pipes (FCHPs) and variable conductance heat pipes (VCHPs) subjected to various acceleration levels from 0 to 1-g. Repriming rates for deprimed heat pipe wicks and the effect of excess working fluid on heat pipe thermal performance will be investigated.

The nutation divergence set of tests will determine the exponential time constants for the divergence of nutation induced by working fluid acceleration in spinning circumferential heat pipes. The effects of heat pipe fill fraction, spin-to-transverse inertia ratio of the model, axial distance from the heat pipes to the model cg, and combining circumferential heat pipes will be studied.

3.3 EXPERIMENTAL APPARATUS CONCEPTS

Apparatus for the experiment disassembles for stowage in two standard orbiter middeck locker drawers. By using a versatile apparatus which easily assembles in two configurations, both thermal performance and nutation divergence tests, defined above, can be conducted with the same basic apparatus.

A substantial portion of the hardware design was derived from the Hughes Fluid Dynamics Experiment (FDE) flown on STS 51-L, the final Challenger flight. The FDE went through the STS flight certification process which was in use at that time. Information gained in that process will be used to improve the current experiment, making it safer and easier to perform than the FDE. All hardware is designed for safety and ease of assembly, operation, and restow, while meeting all requirements necessary to obtain the desired test data. The following guidelines apply for middeck experiments:

1) The total mass of the hardware is not to exceed 22.7 kg (50 lb.) per locker drawer.

2) The mass of each assembly which must be manipulated by a crew member for purposes other than assembly is not to exceed 9.1 kg (20 lb.).

3) The hardware, when disassembled, must stow easily in two standard middeck locker drawers with adequate margin for packing foam.

4) The operational envelope required by the hardware must not exceed the space reasonably available in the middeck area and must not interfere with the operations of the STS or other payloads.

5) The temperatures reached by surfaces of the hardware which are accessible to the crew must not exceed 45 °C (113 °F).

6) The electrical power consumed by the hardware is limited to 115 Watts, 5 Amps maximum per middeck locker.

7) The thermal dissipation required by the hardware shall be less than 115 Watts per middeck locker.

8) The use of flammable materials will be minimized, All flammable materials used must meet the requirements of NSTS 1700.7B paragraphs 209.2 through 209.3.

9) No likely ignition sources shall be used in the design. Any remotely possible ignition source will be used only when necessary, and only when accompanied by corrective measures adequate to prevent the occurrence of ignition.

10) The design will contain no appreciable quantities of materials with toxic, caustic, or otherwise deleterious properties or products (of off-gassing or combustion).

11) All hardware elements will be easily identifiable, easy to manipulate, easy to assemble/disassemble, easy to operate, and easy to destow/restow. The time required for assembly and disassembly should not exceed 30 minutes including margin for experiment contingencies.

3.3.1 Thermal Performance Hardware

The hardware used in the Thermal Performance tests is depicted in Figure 5. The heat pipes mount in sets of four on a spin fixture with the condenser sections radially outward from the evaporator sections. Electric warmers attach to the evaporator sections, and reversible thermo-chromic liquid crystal temperature sensors mount along the length of each heat pipe to determine the wall temperature gradients. An 8 mm video Cam/Corder is used to record the color changes of the temperature sensors.

The spin fixture consists of a cruciform structural support, a motor module, and a control module. The cruciform, and cases for the two modules are made of Lexan^R. The whole apparatus attaches to the middeck lockers frame using an aluminum adapter plate with quick-release fasteners. The spin fixture is powered using the orbiter DC electrical supply and uses a low-torque motor to spin the heat pipes at angular speeds of up to 3.33π radians per sec (100 rpm). The electrical design meets the requirements of JSC Letter ER-87-326, Protection of Power Distribution Circuitry, by using the proper electrical fuses and redundant temperature limiting switches. When fully assembled, the entire apparatus is protected by a safety shroud which prevents accidental contact with the rotating and/or warm hardware.

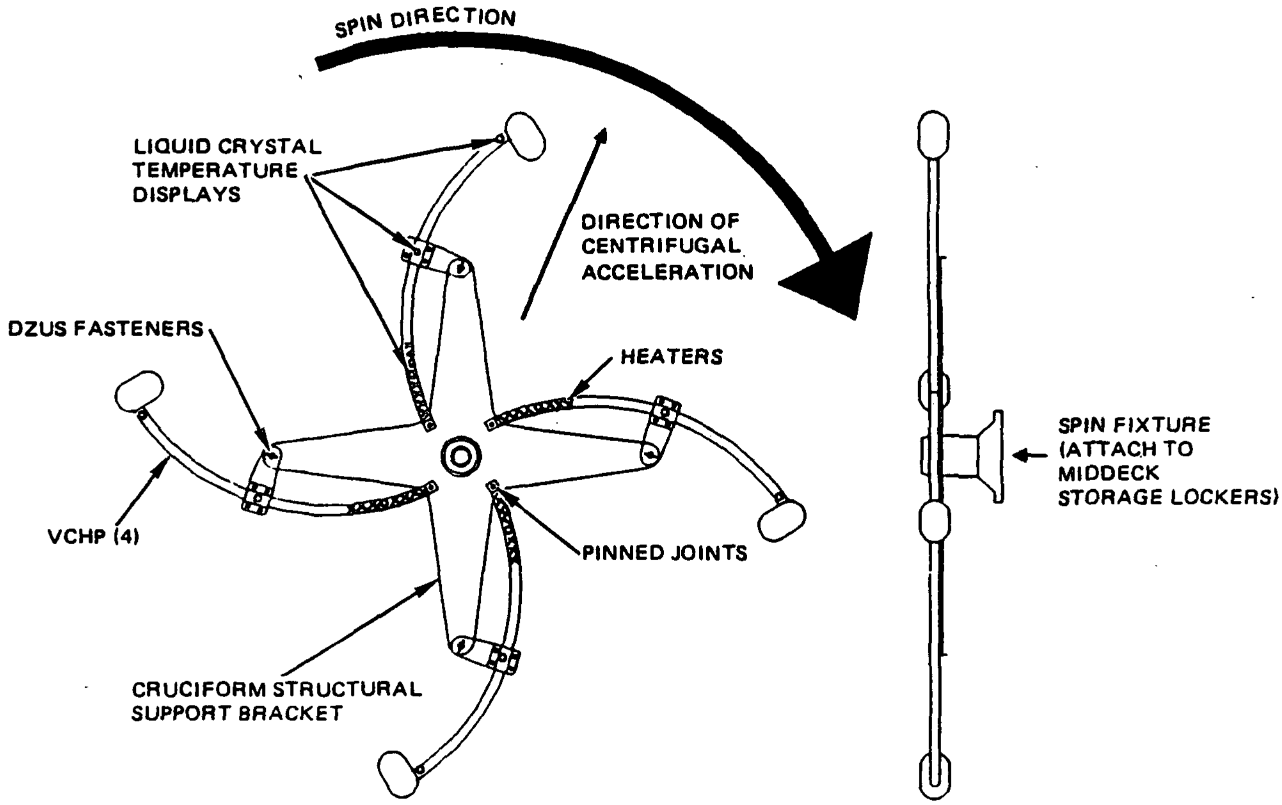

Figure 5 Thermal performance/rewicking apparatus concept illustrated with variable conductance heat pipes.

3.3.2 Nutation Divergence Hardware

The hardware used in the Nutation Divergence tests is illustrated in Figure 6. It is the same basic hardware used in the thermal performance test, except that the heat pipes are swiveled around to form a hoop and connected end-to-end, and the motor and control modules are replaced with the nutation divergence instrument module. The instrument module, which is made of Lexan®, contains an accelerometer, a transmitter, a Lexan® battery pack with 12 AA alkaline batteries, and infrared light emitting diodes (LEDs).

The model (instrument module, cruciform, and heat pipe hoop) is spun up to roughly 3.33π radians per sec (100 rpm) using spin rods protruding from each end. After the translational motion is removed using hand-held Teflon® bearings, the model is released as a free-flier and allowed to spin in the middeck area. The spin speed will be verified using an optical tachometer, and an 8 mm video Cam/Corder will record the entire test.

When the model is spinning freely in the micro-gravity environment, the accelerometer generates a signal due to the model's nutation. This signal is relayed through the LEDs to a receiver powered by two 9 Volt alkaline batteries. The receiver is connected to a data recorder (a standard Walkman® stereo cassette recorder); both units mount with velcro to a convenient middeck surface.

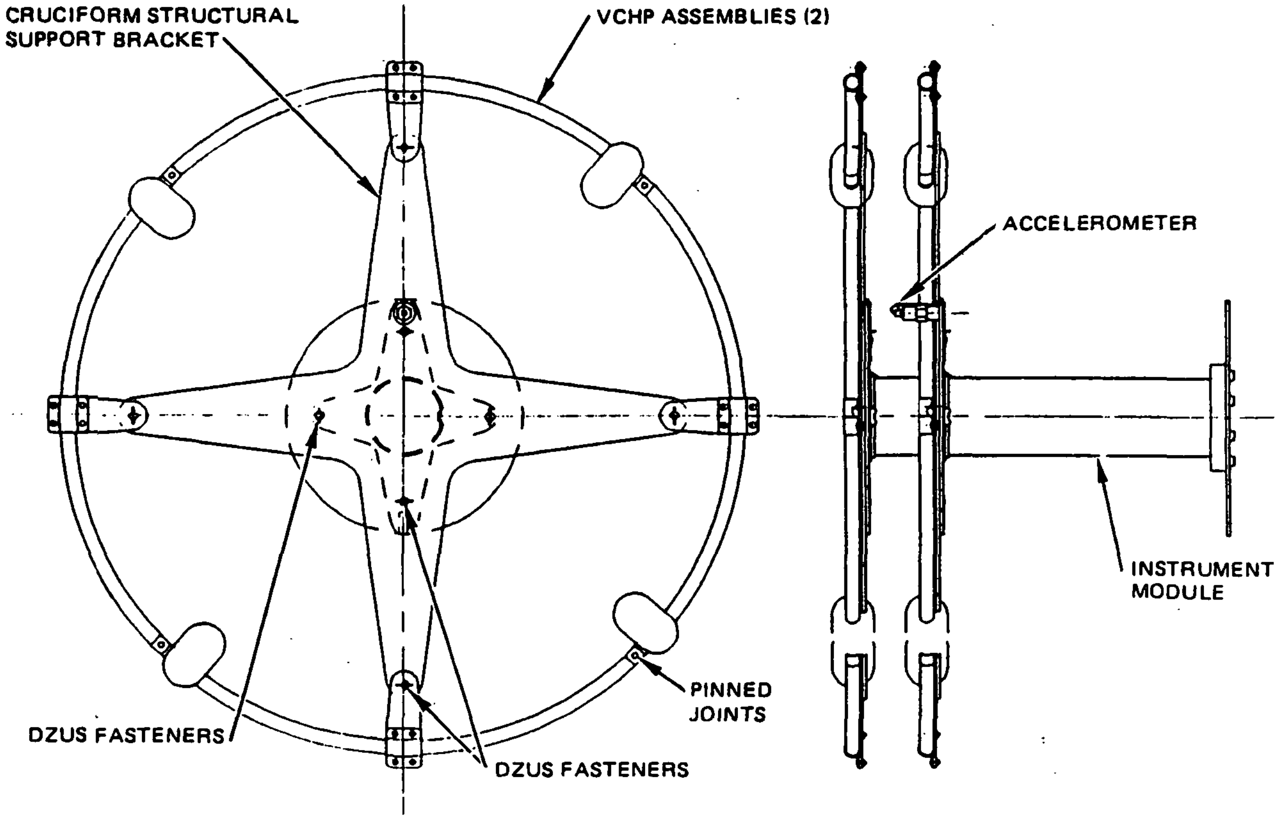

Figure 6 Nutation divergence apparatus concept illustrated with two variable conductance heat pipe hoops (free-flyer).

4.0 EXPERIMENT LOCATION

4.1 BACKGROUND

Both the Nutation Divergence and Thermal Performance apparatus design concepts were derived from the Hughes Fluid Dynamics Experiment (FDE) flown on STS 51-L, the final Challenger flight. The Nutation Divergence apparatus, however, used tank-like modules in place of heat pipe hoops. The previous designs were made so that each apparatus could be stowed in a middeck locker drawer, assembled by a crew member during flight, and operated in the shuttle middeck area (Figures 7 and 8). Consistent with the design of the Thermal Performance apparatus, prototype heat pipes were fabricated and tested. So at the very outset of Phase B development, hardware designed for middeck stowage and operation had pre-existed.

4.2 SUMMARY OF ASSESSMENTS

Although hardware had been fabricated to be located in the middeck area, there had not been a formal selection process by which an experiment location had been identified. In an attempt to not only identify but also justify the optimum experiment location, several assessments were made during Phase B of this program. These assessments included a benefits versus drawbacks matrix, a cost and schedule impact study, a discussion of key issues, detail considerations, a middeck versus cargo bay trade study, and a cost breakdown for cargo bay location. The benefits versus drawbacks matrix, Figure 9, lists both benefits and drawbacks of locating the experiment in the middeck and in the cargo bay. The cost/schedule impact study, Figure 10, provides perceptions of the impact of both cost and schedule if the combined experiment (Nutation and Thermal Performance) was located exclusively in the middeck or cargo bay, or perhaps, split where the Nutation portion would reside in the middeck while the Thermal Performance portion would be in the cargo bay. The key issues discussion, summarized in Figure 11, presents analyses of issues pertaining to experiment operation, environment, size, and safety. The list of considerations, Figure 12, document some additional concerns of the experiment location. The middeck versus cargo bay trade study, Figure 13, presents some principle concerns in point-counterpoint format. The cost breakdown for experiment cargo bay location, Figure 14, provides an estimated cost detail for locating the experiment in the cargo bay.

4.3 CONCLUSIONS

It was concluded from the assessments performed that the shuttle middeck is the optimum location for the experiment based on three key criteria: cost, schedule, and manifesting flexibility. The decision to store and perform the experiment in the middeck area simplifies the hardware by constraining its mass, volume, temperature, electrical power, thermal dissipation, materials, and complexity.

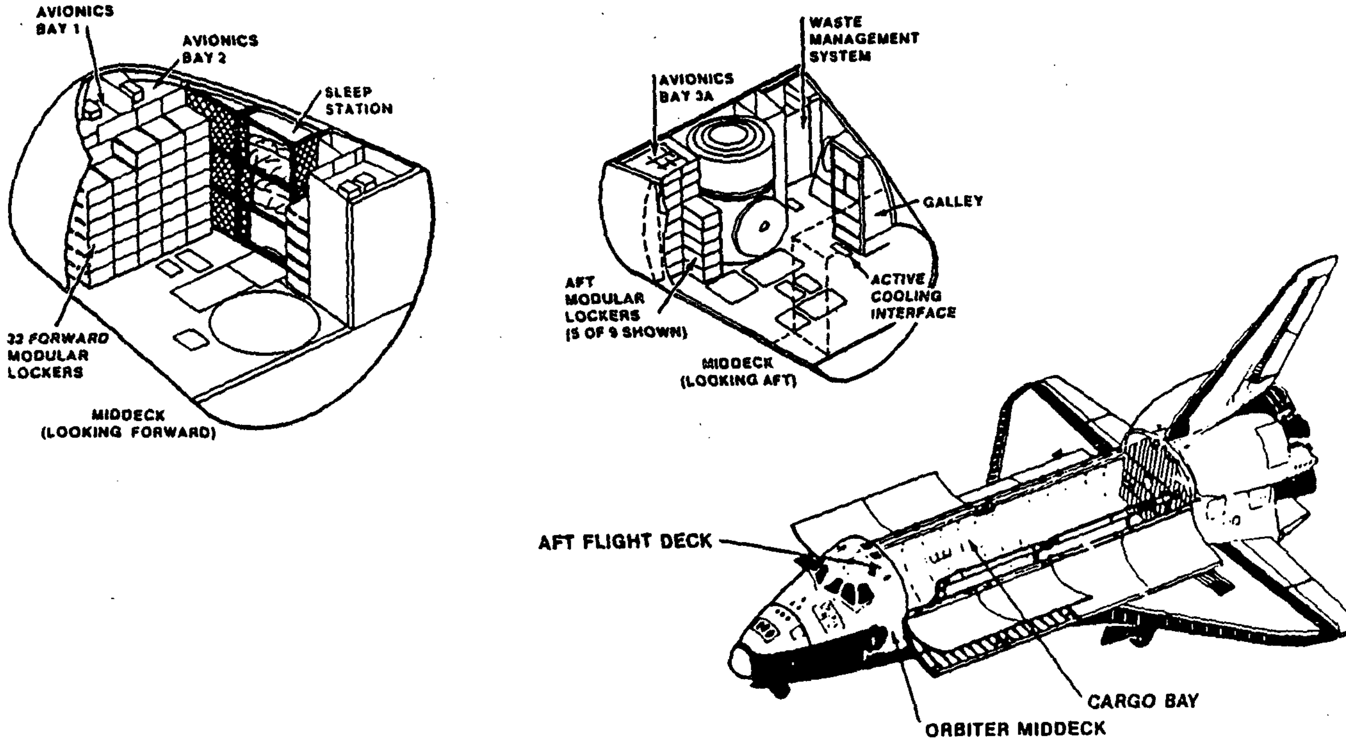

Figure 7 STS shuttle orbiter middeck.

Figure 8 Shuttle middeck lockers.

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EXPERIMENTS IN MIDDECK

BENEFITS	DRAWBACKS
o Easy hand operation (Nutation only)	o Imposes safety requirements which may inhibit quality of data acquired
o Ready access to back-up interfaces such as power and data recording	o Sole dependance on human operator (astronaut) for assembly, test and data acquisition
o Easy operation of data acquisition	
o Flexibility for data checkout and/or verification (test repetition, camera angle, etc.)	o Size limited by drawer capacity
o Minimum cost design, fabrication, and implementation	
o Meets current schedule constraints	
o Provides for change of primary ground test parameter - gravity	

EXPERIMENTS IN PAYLOAD BAY

BENEFITS	DRAWBACKS
o Provides for improved test significance	o Sole reliance on electronics for test operation and data acquisition
o Provides for increased space and weight requirements	o Requires qualification testing to validate survivability of experiment module with respect to shuttle environments
o Test autonomy (experiment, test operation electronics and data acquisition electronics reside in same environmental envelope)	o Imposes ground thermal vacuum testing
	o Requires design and fabrication of an environmental shroud
o Less stringent safety requirements (i.e. higher temperatures, etc.) may lead to quality data	o More complex mechanisms to perform experiment (Nutation only)
	o Does not meet current schedule constraints
	o Increased cost of design, fabrication, and implementation (see text)

Figure 9 Benefits versus drawback matrix.

Cost/Schedule Impact:
For experiments in middeck

Cost Impact: No charge for astronaut training, benign environment simplifies hardware, current estimates are still realistic.

ROM Costs:

Conceptual Design - Completed
Electronic Design - As Bid
Mechanical Design - As Bid
Structural/Thermal Analyses - Detailed Analysis not Required
Environmental Testing - Rigorous Testing not Required

Schedule Impact: All current milestones are attainable, based on prior experience with middeck experiments.

For Nutation experiment in middeck and heat pipe experiment payload bay

Cost Impact: $800 K to $1M due to revised experiment conceptual design, redesign of spaceflight hardware (electrical and mechanical), design of new hardware (structural, thermal control, command, data acquisition/storage), detailed structural and thermal analyses, rigorous environmental testing.

ROM Cost Increases:

Conceptual Design - $20K
Electronic Design - $500 K to $700 K
Mechanical Design - $250 K
Structural/Thermal Analyses - $10 K
Environmental Testing - $20 K

Schedule Impact: Minimum 6 months to expand current design team, assimilate STS payload bay interface documentation, generate conceptual design. Possible 3 additional months required for analyses and testing.

For experiments in payload bay

Cost Impact: $1 M to $1.5 M due to total revision of experiments and hardware required by automation of functions originally conceived of for astronauts, inclusion of fault protection, design of all new hardware, detailed analyses, environmental testing.

ROM Cost Increases:

Conceptual Design - $20 K to $45 K
Electronic Design - $700 K to $1 M
Mechanical Design - $250 K to $425 K
Structural/Thermal Analyses - $10 K
Environmental Testing - $20 K

Schedule Impact: Minimum 1 year including the factors listed for middeck/payload bay split, also additional time required to attain current level of design maturity for all experiments.

Figure 10 Cost/schedule impact study.

Discussions of four (4) key issues:

1. Issue: Astronaut versus automated experiment operation

   Discussion: The current experiments are designed to be simple and easy to operate. Human operators tend to be more resourceful than automatic systems. To fully automate the current experiment requires new circuits and hardware to be designed and built (= higher costs and delayed schedules). Another advantage of the current designs are that several crews have been briefed on similar hardware; thus a number of astronauts are already familiar with the design. The feedback received from those with flight experience is that the tests are well-designed and should be easy to perform. Recently JSC has asked that middeck experiments require more hands on involvement; they feel that one unique advantage of the middeck is that it permits direct human interaction with an experiment. JSC has advised that for an experiment of our complexity, there is no significant charge for astronaut training.

2. Issue: Atmospheric versus vacuum environment experiment operation

   Discussion: There is no clear advantage to a vacuum environment for the current experiments. The middeck provides a controlled environment with temperatures and pressures comparable to our ground test environment. This is important, since one of the goals is to ascertain the effect of microgravity by comparison with testing in a one-g environment. Significant savings are anticipated from use of low cost off-the-shelf hardware such as the data recorder and cam/corder, both designed for a "shirtsleeve environment" rather than custom designing and qualifying expensive hardware designed to operate in an open payload bay, or even sealed in a GAS or CAP can.

3. Issue: Experiment size constraints of middeck versus payload bay

   Discussion: There is no clear advantage in making the hardware larger or heavier. In fact there is a distinct disadvantage in manifesting flexibility. If a GAS or CAP can is used it would actually require scale down of our hardware (for example, the wicking test would decrease from a 34" assembled diameter to less than 19.75", thus requiring spin speed to increase by a factor of 3). The middeck provides adequate space to conduct the current set of experiments. Prior experience has been obtained with one of the orbiter simulators at JSC while planning procedures for a similar middeck experiment.

4. Issue: Experiment safety constraints of middeck versus payload bay

   Discussion: The safety requirements of the middeck are easily met by our present design, including requirements for flammability, toxicity, and battery power systems.

Figure 11 Key issues discussion.

- The experiments were originally proposed as Middeck experiments. The designs were sufficiently advanced to win a Development award, thus to change to the payload bay requires that the new designs be at least as mature as the current one, implying significant redesign which means added cost and schedule slips.

- Most of the current team's experience is with Middeck experiments.

- Most of the current team's background is in mechanical and thermal design. Modifications of the experiment concept for the payload bay (timing, electric heating, data recording) will require early participation by electrical/electronic engineers which will contribute to increased costs and result in schedule slips. Additional changes such as thermal design and structural support will consume additional program resources.

- The Nutation Divergence test is simple when performed in the middeck by human operators, but would require extensive redesign to perform automatically.

- The current design has a minimum impact on orbiter capabilities (mass, volume, power, thermal control, attitude control) which makes it easier to manifest.

Figure 12 List of considerations.

Astronaut Involvement

Mid-deck
Astronaut attention is required; hands-on involvement can salvage experiment if problems develop

Cargo bay
Minimal attention required; minimal ability to save experiment that fails

Space Test Conditions

Mid-deck
Zero-g; earth standard atmosphere and thermal conditions

Cargo bay
Zero-g; vacuum available; wide thermal range possible (must be insulated against if not desired)

Safety Considerations

Mid-deck
No high temperatures, no toxic substances, no mechanisms that could injure astronauts

Cargo bay
Less concern for immediate astronaut danger; still must satisfy outgassing/ thermal/structural requiremnts

Test Volume and Mass

Mid-deck
Must be stowed in 2 cubic feet of locker space and weigh less than 50 lbs

Cargo bay
GAS containers can hold up to 200 lbs in a cylinder 19.75" in diameter and 28" in height; Hitchhiker-G configuration includes a mounting plate and avionics interface

Electronic Design

Mid-deck
Simple on-off switches for astronauts to throw
Camera operated manually

Cargo bay
Complex circuits, stored commands for GAS
Fault detection and autonomous switching to redundant units
Camera needs automatic control

Mechanical Design

Mid-deck
Astronauts mount and stow fixtures
Astronauts may spin up the experiment by hand

Cargo bay
Additional mechanisms could be needed to spin up the experiment

Structural/ Thermal Analysis

Mid-deck
Detailed analysis not required as the thermal environment is benign

Cargo bay
Analysis must be performed during design to insure no thermal distortion occurs due to the wide temperature variations in the bay

Environmental Ground Tests

Mid-deck
Ground tests can be performed in normal laboratory environment

Cargo bay
Ground tests may require a thermal-vacuum test to simulate cargo bay

Figure 13 Middeck versus cargo bay trade study.

COST BREAKDOWN OF ADDED COST
FOR CARGO BAY EXPERIMENT LOCATION

I. Conceptual/Preliminary Design	
Electronic sub-systems:	
Feedback control schemes	50K
Data acquisition schemes	50K
Data storage schemes	50K
Logic schemes	100K
Structural dynamics analysis of experiment apparatus	25K
Thermal/mechanical design of experiment enclosure	30K
II. Detail Design	
Electronic sub-assemblies	
Feedback control circuitry	50K
Data acquisition circuitry	50K
Data storage circuitry	50K
Redundant/back-up/crew bay interface electronics	50K
Logic design (software & firmware)	100K
Breadboarding	100K
Packaging design for electronics	50K
Structural dynamics analysis of experiment enclosure	50K
III. Formal Configuration Management	150K
IV. Hardware Build	
Fabrication of electronic packages	200K
Fabrication of experiment enclosure	100K
V. Qualification Test	
Mechanical dynamics test	100K
Thermal vacuum test	100K
TOTAL	1.5M

Note that effort shown above would require expansion of team to include:

- Analog circuit design engineer
- Digital circuit design engineer
- Software development engineer
- Structural dynamics engineer

Figure 14 Cost breakdown of added cost for cargo bay experiment location.

5.0 HARDWARE EVALUATION

5.1 THERMAL PERFORMANCE GROUND TESTING

The primary focus of ground testing for the thermal performance hardware in Phase B was to evaluate the heat pipe test performance, and demonstrate the methods of data acquisition. This testing was intended to provide confidence that the experiment can be adequately performed.

5.1.1 Test Plan

The thermal performance ground test plan addressed three key areas: 1) Thermochromic Liquid Crystal (TLC) usage for temperature measurement, 2) video recording for data acquisition, and 3) heat pipe performance characterization and operation while rotating.

5.1.1.1 Thermochromic Liquid Crystal (TLC) Usage

Purpose: The purpose of the TLC usage definition activity was to establish TLC application procedures, color/temperature accuracy, detection sensitivity level, and interpretability level from video recordings.

Hardware: One or two, copper or aluminum, thin (less than 1/8-in. thick) 2-in. diameter circular swatch sample disk(s), one-10 in. length monel circuit card type heat pipe, one VCHP (Figure 4), one 36-in. diameter turntable made of plywood, variable speed motor capable of 100 rpm, heaters, DC power supply, Airbrush.

Instrumentation: TLC material (slurry, coating, adhesive film), thermocouples, thermocouple readout device, video cam/corder, video light.

Procedure: Using the circular swatch sample disk(s), several "pie" segment applications of TLC in slurry, coating, and adhesive form shall be made. With a single thermocouple at the disk's center and heat applied at its back surface, calibrations of color versus temperature shall be made.

Using the monel circuit card type heat pipe, 1/4 in. wide, lengthwise bands of slurry, coating, and adhesive shall be made on one surface of the heat pipe. On the opposite surface shall be a 2 in. heater length with thermocouples along the remaining length. With the evaporator end at various elevations above the condenser end, the TLC detection sensitivity level shall be evaluated. In addition, viewing of the heat pipe shall be made using the video camera at various viewing

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angles (i.e. 15, 30, 60 and 90 degrees above horizontal) and with the camera light turned "off" and "on". Using the monel tubing, a smooth wall water "heat pipe" shall be made. Application of TLCs shall be made at three locations along the tube length. This test article shall be used to evaluate slug detection of the TLCs.

Using the VCHP, application of TLCs shall be made at three locations along the tube length. This test article shall be rotated on the turntable with the motor. Viewing of the test article shall be made via the video camera to evaluate the interpretability level of the TLCs from video recordings.

5.1.1.2 Data Acquisition Evaluation

Purpose: The purpose of the data acquisition evaluation activity is to validate the key methods of performing the experiment while acquiring the data. The key methods are: observing and recording TLC operation on prototype hardware; retrieving temperature information from the recorded video and comparing with thermocouple measurements; and observing the heat pipe depriming capability of the spin apparatus at the desired spin speed.

Hardware: One FCHP (Figure 3), one VCHP (Figure 4), plywood turntable, AC motor, Variac for motor speed control, heaters, mercury filled type slip ring assembly, DC power supply.

Instrumentation: TLC material, strip chart recorder, thermocouples, video cam/corder, video light, mechanical hand held type tachometer.

Procedure: Mount one VCHP and one FCHP fully instrumented with thermocouples, TLC material, and heaters to the motorized turntable. Rotate turntable at 100 rpm in horizontal plane. Perform re-wicking tests and dry-out tests while recording temperatures via strip chart recorder and video camera.

5.1.1.3 Heat Pipe Preliminary Performance Characterization

Purpose: The purpose of this activity is to gain a sense of the performance range of the prototype hardware.

Hardware: One FCHP (Figure 3) with thermocouples, TLCs and heaters mounted, DC power supply.

Instrumentation: Strip chart recorder, current or wattmeter.

Procedure: One FCHP, one fill inventory of water, three tilts, 50 °C maximum, 45 W maximum; one VCHP, one fill inventory of water, three tilts, 50 °C maximum, 45 Watts maximum. Perform re-wicking test.

5.1.2 Test Results

A photograph of the turntable used to test heat pipe performance and data acquisition techniques at various spin rpms is shown in Figure 15. The FCHP, VCHP, and slip ring assembly used to transmit power to the electrical heaters and thermocouple signals to the chart recorder are visible in the photograph. Note that the VCHP was bent into the curvature of the final hoop configuration, whereas the FCHP was not.

Ground testing of the thermal performance hardware provided the following data and insights:

- TLC coating and slurry application takes skill and care to achieve proper thickness for accurate temperature measurement.
- TLC temperature calibration after application is necessary to achieve proper readings.
- TLC video recording is acceptable while stationary but marginal while moving at high rpms (>60 rpm).
- Test article maximum temperatures with 40 watt evaporator heat load, no tilt, and fan directed on condenser were 55°C for the FCHP and 40°C @ 25 W dry-out gradient of 10°C for the VCHP.
- Rewicking test was successfully accomplished.

Ground test heat pipe performance results are summarized in Tables 1 and 2.

5.1.3 Conclusions

It can be concluded from the thermal performance ground test data, that TLCs can be successfully used to indicate temperature provided they are calibrated prior to use. The heat pipes can be successfully operated while rotating, but still photography should supplement video recording for data acquisition. Additional video testing at low rpms and various lighting conditions will be required in Phase C/D.

The temperature maximums for the test articles exceed the maximum safe contact temperature of 45 °C, imposed upon the experiment, for most of the operational scenarios. Hence, a fan and a safety barrier will be integrated into the experiment. The

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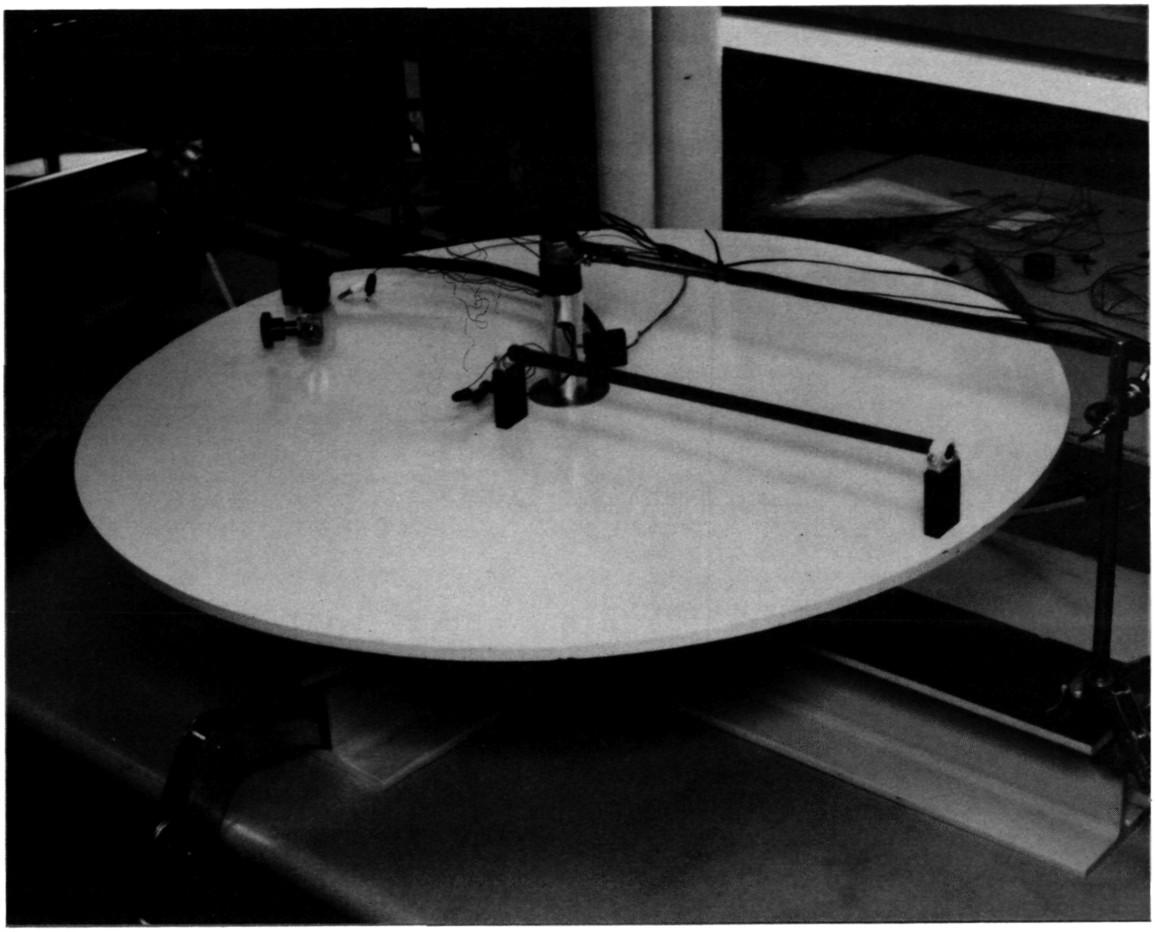

Figure 15 Spin table for heat pipe ground testing.

TABLE 1

CHARACTERIZATION TEST RESULTS

Heat Pipe Type*	Heater Power (Watts)	Pipe Tilt (inch)	Temperatures	
			Peak (°C)	Max T (°C)
VCHP	10	0	53	1.5
	20	0	72	2.3
	30	0	96	3.0
	40	0	112	3.0
	45	0.25	164	4.0
	45	0	120	3.0
	40	0	68**	19.5
FCHP	8	0	50	1.5

* VCHP: VARIABLE CONDUCTANCE HEAT PIPE
FCHP: FIXED CONDUCTANCE HEAT PIPE

** With fan.

TABLE 2

EXPERIMENT PERFORMANCE EVALUATION RESULTS

Heat Pipe Type*	Heater Power (Watts)	Fan	Rotation Speed (rpm)	Temperatures	
				Peak (°C)	Max T (°C)
VCHP	10	Off	0	47	<1
	20		0	71	<1
	40		0	110	2
	10		25	44	12
	20		25	66	20
	40		25	110	37
	10		50	63	40
	20		50	106	40
	40		50	>170	>140
	10		100	58	36
	20		100	94	72
	40		6	106	4
	20		6	70	2
VCHP	40	On	0	73	36
	20		0	37	7
	25		0	40	10
	20		6	40	6
	40		6	74	27
	20		12	42	8
FCHP	10	Off	0	33	<1
	20		0	90	<1
	40		0	142	1
	10		25	90	60
	20		25	146	110
	10		50	84	58
	20		50	140	112
	10		100	124	100
	40		12	128	6
FCHP	40	On	0	55	2
	40		6	72	<1
	40		12	72	4

* VCHP: VARIABLE CONDUCTANCE HEAT PIPE
FCHP: FIXED CONDUCTANCE HEAT PIPE

safety shroud will be designed in Phase C/D to prevent physical injury as well as temperature contact. It will also be necessary to re-size the dimensions of the wicks and grooves to optimize performance for the working fluid (water) and operating temperatures of interest for this experiment.

5.2 KC-135 Flight Testing

The infrared telemetry system for the Nutation Divergence experiment is based on hardware previously designed for the Hughes Fluid Dynamics Experiment (Section 4.1). One set of this hardware was successfully flown on the NASA KC-135 free-fall training aircraft, proving out the infrared telemetry data acquisition and video taping techniques.

Another opportunity to fly a mockup of the Nutation Divergence Apparatus on the KC-135 aircraft occurred during Phase B of the current program. This testing was directed toward the spin-up, release, and capture techniques in a low-gravity environment. Two methods for spinning-up and release were evaluated:

- Spin-up cord
- Cordless screwdriver

Figure 16 shows Robert N. Stuckey of NASA Johnson Space Center holding the mockup spin rods between two Teflon blocks while an assistant pulls the spin-up cord. The spin-up cord was attached to the instrument module with Velcro, and then wrapped around it several times. Pulling this cord while restraining the spin rods causes the model to spin-up. The behavior of the mock-up was photographed (Figure 17) and video taped in low gravity conditions on-board the KC-135 aircraft. These results were compared with those using a cordless screwdriver for spin-up, as shown in Figures 18 and 19.

It was concluded from the KC-135 flight testing that the cordless screwdriver was easier to use and resulted in a smoother release of the apparatus in low gravity conditions. The most notable difference was that it was possible for only one person to spin-up and release the apparatus using the cordless screwdriver, whereas two crew members were required to use the spin-up cord.

Figure 20 is a photograph of the nutation divergence mockup next to the middeck lockers in the middeck mockup facility at the Johnson Space Center. We plan to make extensive use of this facility for planning and training purposed in Phase C/D of this program.

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Figure 20 is a photograph of the nutation divergence mockup next to the middeck lockers in the middeck mockup facility at the Johnson Space Center. We plan to make extensive use of this facility for planning and training purposed in Phase C/D of this program.

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Figure 16 Nutation divergence mock up in KC-135 aircraft, showing spin-up cord technique.

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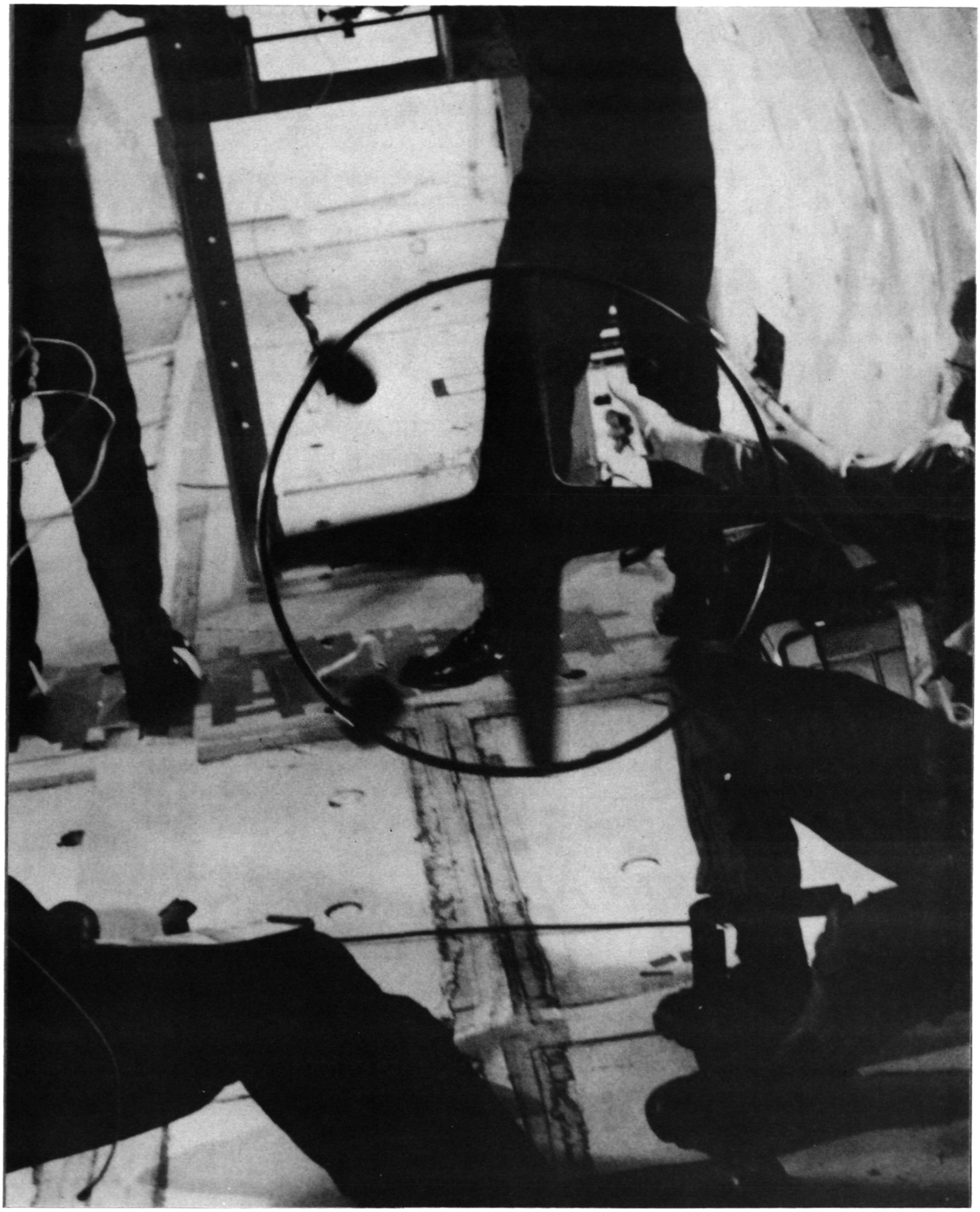

Figure 17 Nutation divergence mock up in KC-135 aircraft (spin-up cord launch).

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Figure 18 Nutation divergence mock up in KC-135 aircraft showing cordless screwdriver technique.

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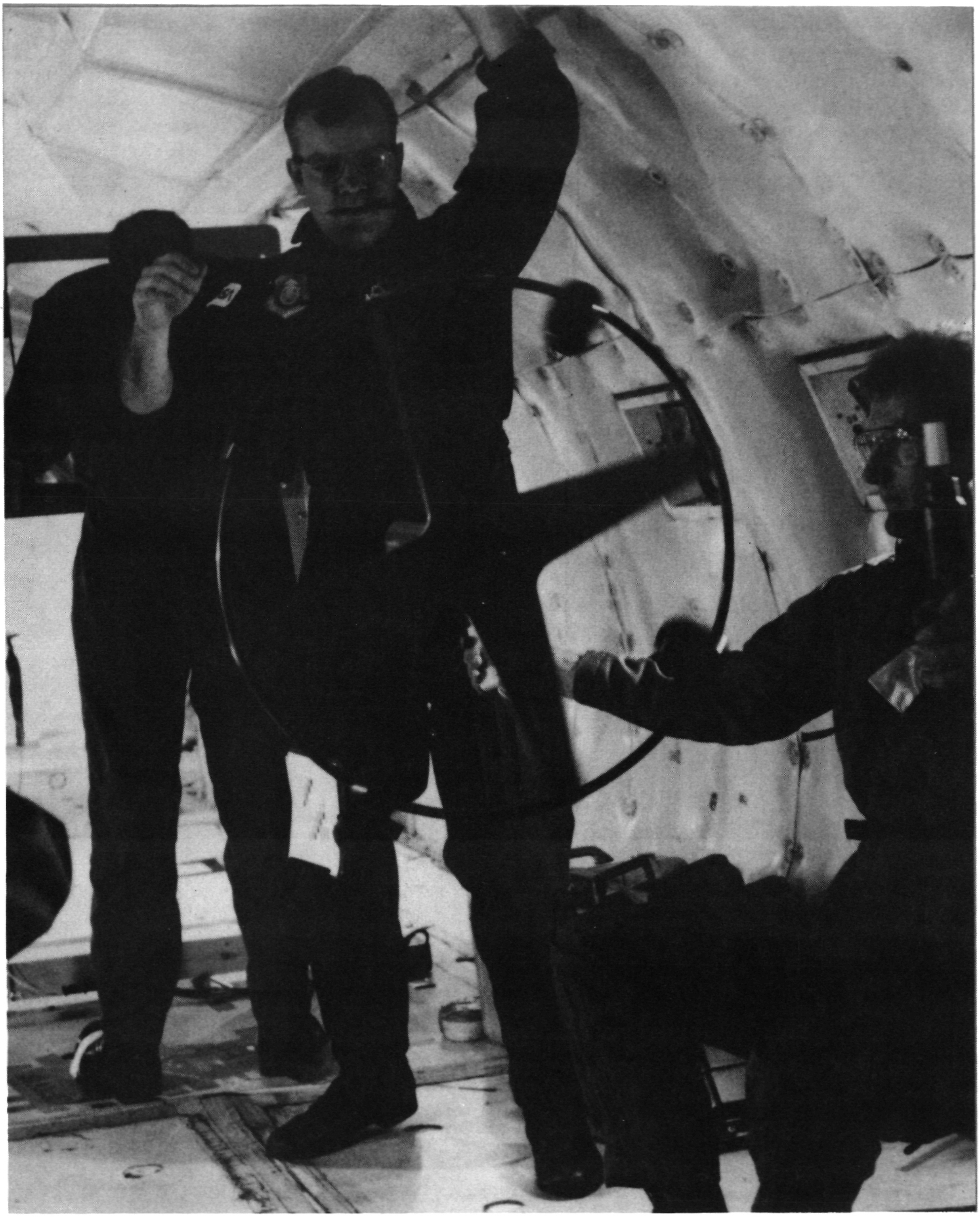

Figure 19 Nutation divergence mock up in KC-135 aircraft (cordless screwdriver launch).

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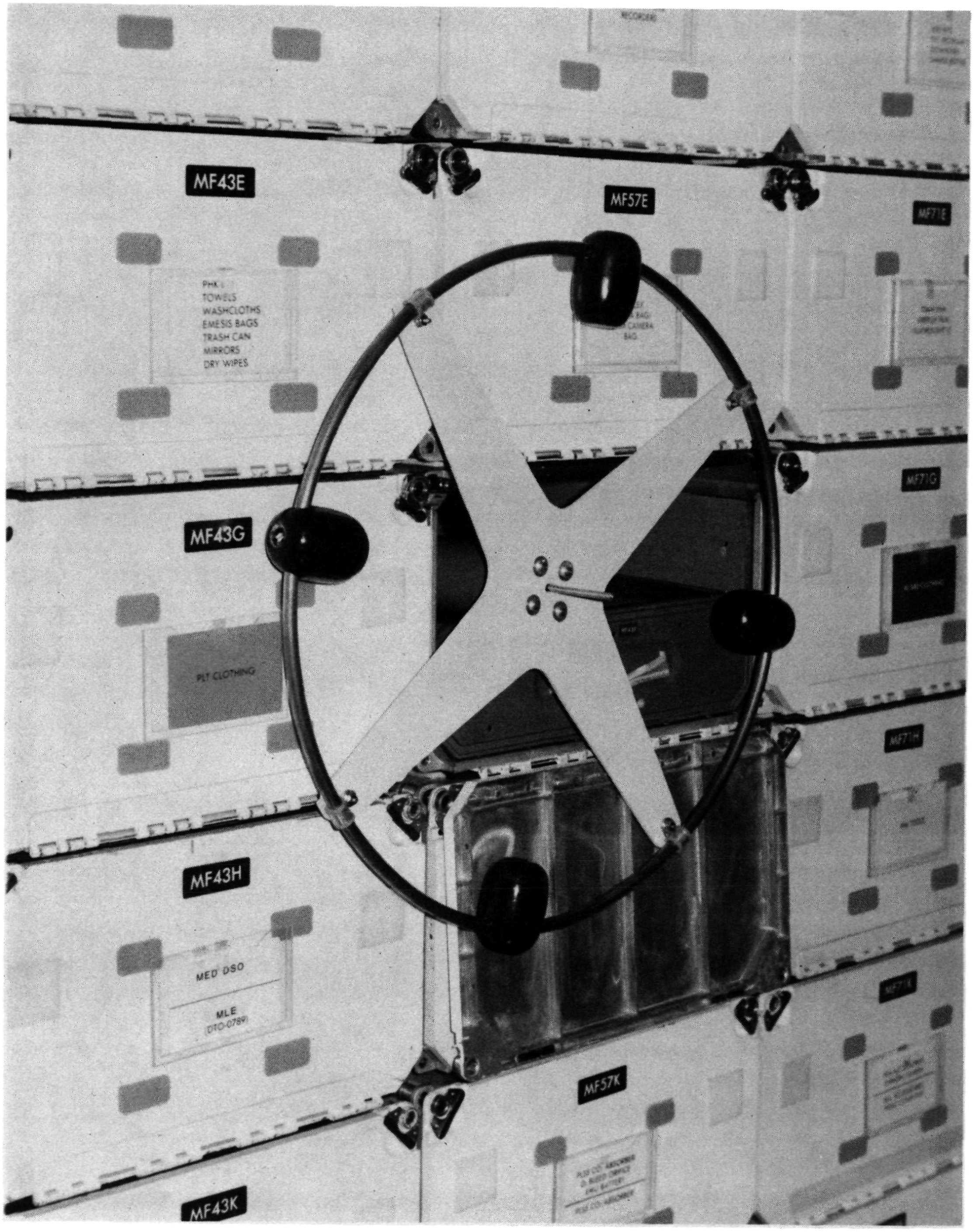

Figure 20 Nutation divergence mock up next to middeck locker, in the middeck mock up facility at JSC.

6.0 EXPERIMENT APPARATUS DETAIL DESIGN

6.1 THERMAL PERFORMANCE APPARATUS

A layout drawing of the experimental apparatus for in-space thermal performance and wicking recovery testing is shown in Figure 21. Figure 22 is an isometric drawing of the apparatus. The hardware required to produce this apparatus is listed in Table 3.

6.1.1 Heat Pipes with Attach Brackets

The flight heat pipes will be made of monel with triply distilled water as the working fluid. There will be two (2) sets of FCHPs and two (2) sets of VCHPs for a total of sixteen (16) heat pipes. Note that each set consists of four (4) heat pipes, and each pair of heat pipes will be processed with a different fill fraction of working fluid. The VCHPs have a porous central core knitted mesh wick inside which is made of copper, whereas the FCHPs have axial grooves machined directly into the wall material for capillary pumping of the working fluid. The VCHPs also have a noncondensable gas reservoir at the condenser end, whereas the FCHPs do not. However, for this series of experiments, the heat pipes will not have noncondensable gas inside them. This will allow us to more clearly observe the effects of excess liquid on heat pipe performance. Heat pipe details are summarized in Table 4.

6.1.2 Electrical Warmers

Low power etched-foil element, Kapton^R insulated, type electric resistance warmers will be pre-bonded to the evaporator of each heat pipe to provide heat input for thermal performance experiments. Warmer circuits will include circuit breakers and temperature limiting thermostats. Power will vary from 0 to a maximum of 60 Watts, and only one heat pipe will operate at a time. Therefore,the current through the slip ring assembly, described in paragraph 2.1.8.1, will never exceed 2.14 Amps for a 28V DC power supply. Two (2) 1.0 in. X 3.0 in. warmers, as specified below, will be wired in parallel to achieve these power requirements for each heat pipe. They will be bonded to the heat pipe surface with pressure sensitive adhesive and overwrapped with Kapton^R tape to provide an evaporator length of 6.0 inches.

Manufacturer:	Minco
Part Number:	HK-5165-R26.1-L12-B
Resistance (Ohms):	26.1
Max. Power (Watts):	30 Each
Dimensions (in.):	1.0 X 3.0
Quantity:	2 per heat pipe
Weight (lb.):	0.01 Each

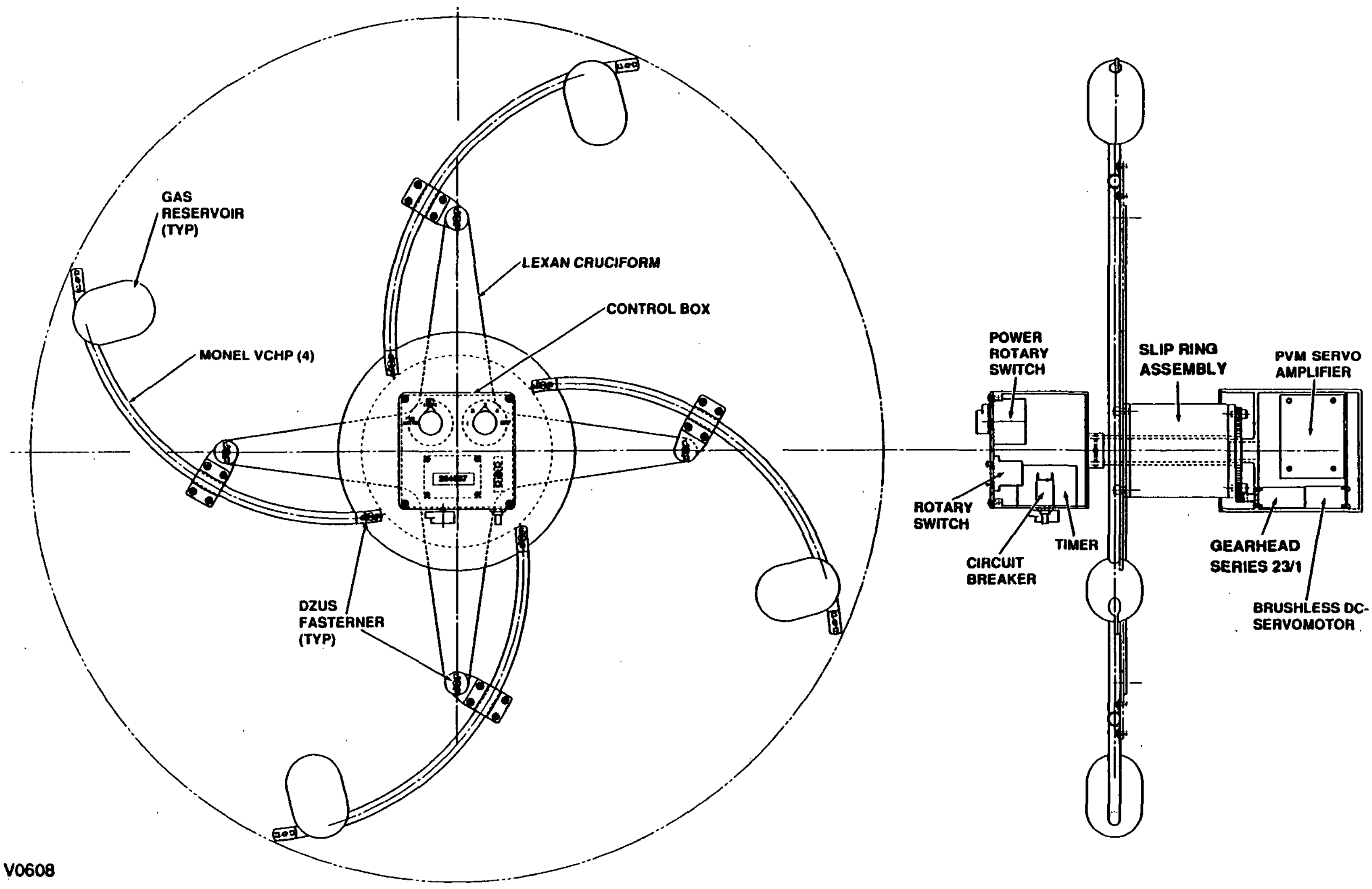

Figure 21 Thermal performance apparatus layout drawing.

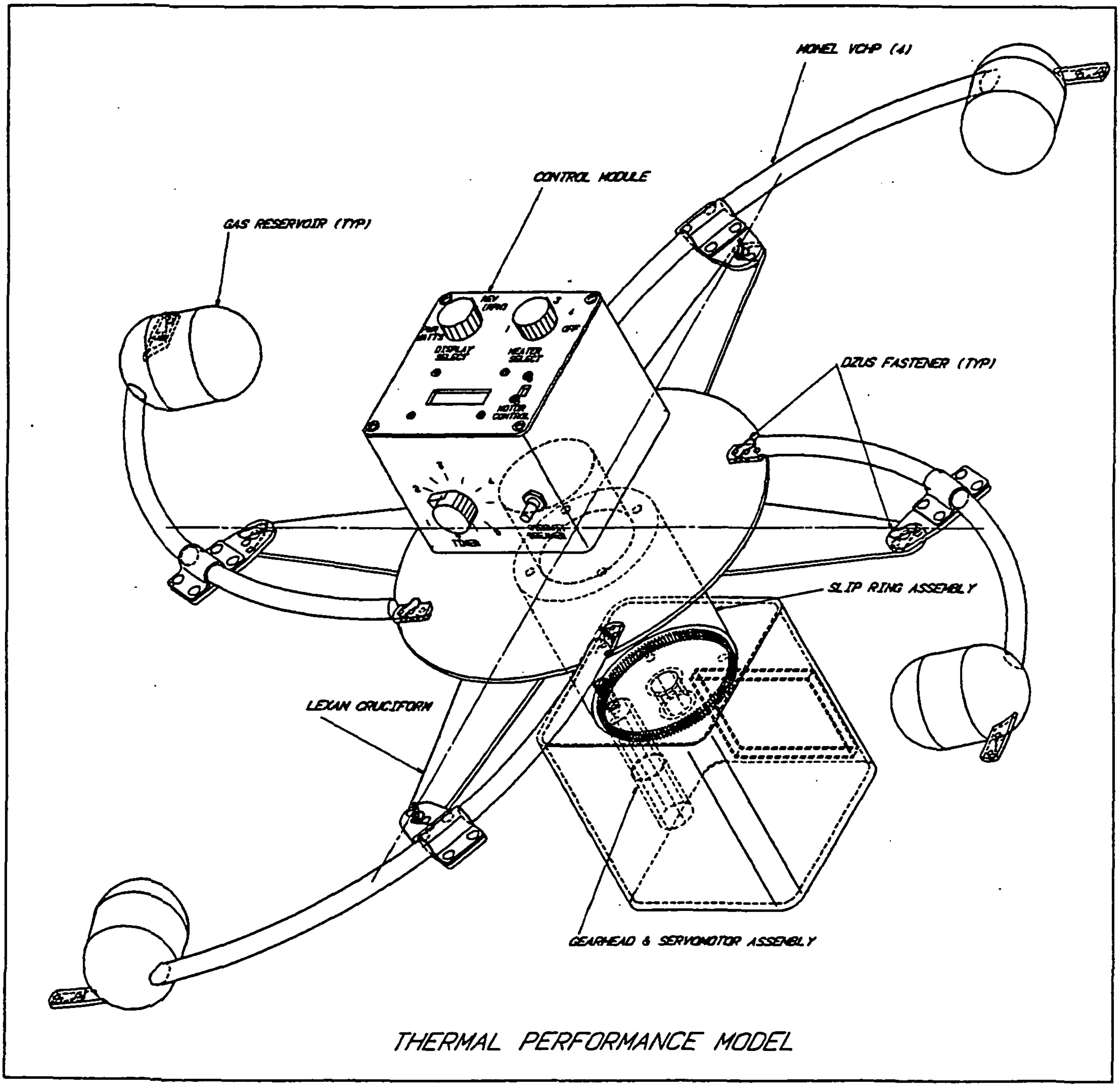

Figure 22 Thermal performance apparatus design.

TABLE 3

LIST OF HARDWARE FOR
THERMAL PERFORMANCE TESTS

REF.	DESCRIPTION	QTY.	TOTAL WEIGHT (LB.)	POWER (WATTS)
6.1.1	Fixed Conductance Heat Pipes (FCHPs) with Attach Brackets	8[1]	2.5	N/A
6.1.1	Variable Conductance Heat Pipes (VCHPs) with Attach Brackets	8[1]	6.7	N/A
6.1.2	Electrical Warmers	32	0.2	<40[2]
6.1.3	Thermostats	32	0.6	N/A
6.1.4	Temperature Sensitive Liquid Crystal Displays	A/R	0.1	N/A
6.1.5	Cruciform Support with Attachments	1[1]	1.0	N/A
6.1.6	Adapter Plate for Middeck Lockers	1	6.5	N/A
6.1.7	Motor Module			
6.1.7.1	Brushless DC Motor	1	0.5	13.7
6.1.7.2	Gearhead	1	0.18	N/A
6.1.7.3	Servo Amplifier	1	0.25	3.4
6.1.7.4	Slip Clutch	1	0.3	N/A
6.1.7.5	Slip Ring Assembly	1	0.75	N/A
6.1.7.6	Housing	1	0.87	N/A
6.1.8	Control Module			
6.1.8.1	Warmer Selector Switch	1	0.07	N/A
6.1.8.2	Display Selector Switch	1	0.07	N/A
6.1.8.3	Motor Speed Control	1	0.07	N/A
6.1.8.4	RPM/Wattage Read-out	1	0.06	<0.5
6.1.8.5	Warmer Timer	1	0.15	<0.5

TABLE 3 (Cont.)

REF. DESCRIPTION	QTY.	TOTAL WEIGHT (LB.)	POWER (WATTS)
6.1.8 Control Module (Cont.)			
6.1.8.6 Circuit Breaker	1	0.03	N/A
6.1.8.7 Housing	1	0.77	N/A
6.1.9 Brushless DC Fan	1	0.39	3.3
6.1.10 Safety Shroud	1	3.0	N/A
6.1.11 Video Cam/Corder	1 (1)[1,3]	2.5	N/A
6.1.11 Video Tape (8mm Video Cassette)	1 (2)[1]	0.3	N/A
6.1.11 Battery Pack (Special)	1 (2)[1]	1.5	N/A
6.1.11.1 DC Power Supply	1[1]	1.0	15
6.1.11.2 Velcro Attach Fixture	1[1]	0.3	N/A
6.1.12 Video Light	1[1]	0.3	40
6.1.12.1 Power Cord to Power Supply	1[1]	0.1	N/A
6.1.12.2 Velcro Attach Bracket	1[1]	0.2	N/A
TOTAL		31.26[4]	<116.4

NOTES:

1. This item used for both thermal performance and nutation divergence experiments.
2. Only one heat pipe will operate at a time.
3. Numbers in parentheses indicate number of flight spares.
4. This is the total weight of all items for the thermal performance test; see Table 6 for the combined weight of items for both the thermal performance and nutation divergence experiments.

TABLE 4

DESCRIPTION OF EXPERIMENTAL HEAT PIPES

ITEM	FIXED CONDUCTANCE HEAT PIPE (FCHP)	VARIABLE CONDUCTANCE HEAT PIPE (VCHP)
Description:		
Envelope	Circular tubing formed with a 12.0 in radius of curvature to fit one-fourth of a 24.0 in. diameter hoop.	Circular tubing, with gas reservoir at condenser end, formed with a 12.0 in. radius of curvature to fit one-fourth of a 24.0 in. diameter hoop.
Wick	Axial grooves (25) electro-discharge machined in envelope wall.	Porous knitted mesh, central core wick with spacer wicks.
Materials:		
Envelope	Monel	Monel
Wick	N/A	OFHC Copper
Working Fluid	Triply Distilled Water	Triply Distilled Water
Liquid Fill Fractions (%)	90, 100, 110, 120	90, 100, 110, 120
Nominal Dimensions:		
Diameter (in.)	0.5	0.5
Length (in.)	19.0	19.0
Gas Reservoir (in.)	N/A	1.5 OD x 2.0*
Quantity:		
Sets**	2	2
Each	8	8
Weight per pipe (lb.)	0.31	0.84

* VCHPs will not have noncondensable gas inside them for these experiments.

** Each set consists of four (4) heat pipes.

6.1.3 Thermostats

Two (2) bi-metallic thermostat switches shall be bonded near the evaporator of each heat pipe with Stycast^R epoxy. The function of these thermostats is to automatically turn off power to the electrical warmers if the temperature of the heat pipe exceeds a pre-set value; two thermostats are required for redundancy. Temperature calibration is pre-set at the factory, and they are hermetically sealed. They are designed to meet the performance qualifications of MIL-STD-202.

Manufacturer:	Elmwood Sensors Inc.
Series:	3500
Part Number:	3500Y/T120/B210/0
Current Rating (A):	5
Dimensions (in.):	0.605 Dia. X 0.290
Quantity:	2 per heat pipe
Weight (lb.):	0.019 each

6.1.4 Temperature Sensitive Liquid Crystal Displays

Reversible, encapsulated Thermochromic Liquid Crystal (TLC) films will be pre-bonded to each heat pipe for temperature measurement. In this manner the heat pipe temperature distribution can be observed and photographed in real time. TLC displays provide a continuous distribution of the surface temperatures, rather than just discrete points as with other methods such as thermocouples or thermistors. They are specified as follows:

Manufacturer:	Hallcrest
Identification Nos.:	a) Red start temp. >40 °C. b) Red start temp. <40 °C. c) Standard sheets.
Type:	TLC coated polyester sheets.
Temperature Ranges (°F):	TBD
Temperature Sensitivity (°F/Color):	0.3
Bonding Method:	Adhesive back.
Nominal Dimensions (in.):	12 x 12 Sheets.
Weight (lb.):	0.003 Each

6.1.5 Cruciform Support with Attachments

A cruciform structural member will be fabricated of aluminum or Lexan^R and equipped with quick-release fasteners for attachment of the heat pipes (Figure 13). Nominal dimensions and weight specifications are given below:

Manufacturer:	Hughes/Design Models Inc.
Material:	Aluminum or Lexan[R]
Part Number:	TBD
Dimensions (in.):	24.0 OD x 0.25 thick.
Weight (lb.):	1.0

6.1.6 Adapter Plate for Middeck Lockers

An aluminum adapter plate is required for mounting the test apparatus to the rack of middeck lockers. It also acts as a heat spreader plate for the electric motor.

Manufacturer:	Hughes/Design Models Inc.
Material:	Aluminum
Part Number:	TBD
Dimensions (in.):	18.125 x 10.757 x 0.75
Weight (lb.):	6.5

6.1.7 Motor Module

The motor module contains a low EMI, brushless DC electric motor for rotating the heat pipe assembly, a servo amplifier for controlling the motor, a gearhead, a slip clutch for safety purposes, and a slip ring assembly for the transmission of electrical power from the Orbiter 28 VDC bus to the warmers on the rotating heat pipes. The amplifier includes a motor shutoff command, and an overcurrent signal enabling the detection of any defect in the power stage or in the motor. All of these components are mounted inside a polycarbonate housing. The motor and housing are mounted directly to the adapter plate (6.1.6), which also acts as a heat spreader plate for the motor.

6.1.7.1 Brushless DC Motor

This is a three phase dc-servo motor designed to cover a wide range of applications, where motor life, reliability, and size are factors. The rotor uses rare earth magnets for high power to volume and power to weight ratios. Electronic phase commutation is achieved using magnetic solid state sensors.

Manufacturer:	Micro Mo Electronics Inc.
Series:	BL 2444
Part Number:	2444SBL1
Peak Torque (oz.-in.):	9.2
Input Power (W):	13.7
RPM:	0 to 200
Dimensions (in.):	0.944 OD X 1.732, (0.118 Dia. X 0.433 Shaft)
Weight (lb.):	0.5

6.1.7.2 Gearhead

Planetary gearing with nickel plated, steel case and two sealed ball bearings.

Manufacturer:	Micro Mo Electronics
Series:	23/1
Part Number:	23/1, 43:1+X0434
Gear Ratio:	43:1
Rated Output Torque(oz.-in.)	
Continuous:	100 (700 mNm)
Intermittent:	141.6 (1000 mNm)
Dimensions (in.):	0.905 O.D. X 1.433
Weight (lb.):	0.18

6.1.7.3 Servo Amplifier

An electronic amplifier is required for brushless DC motors for power conditioning. Approximately 25% of the power required to run the motor is consumed by the amplifier.

Manufacturer:	Micro Mo Electronics Inc.
Type:	BLD 403
Part Number:	BLD 403
Rated Voltage (VDC):	12-40
Rated Current (A)	
Continuous:	2.5
Peak:	3
Dimensions (in.):	3.583 X 2.756 X 0.807
Weight (lb.):	0.25

6.1.7.4 Slip Clutch

The slip clutch provides protection against accidental overloads, and a safety release in the event of jamming of the motor mechanism. It will slip when a specified torque setting is reached, and resume driving as the load is reduced. The slip clutch is a small precision device containing a number of brass plates interfaced with friction pads. Soft springs maintain pressure on the friction pads for constant torque during normal operation.

Manufacturer:	Polyclutch, Custom Products Corp.
Type:	Mechanical Slip Clutch
Part Number:	SAS-16
Rated Torque Range (oz.-in.):	4.8 to 160
Dimensions (in.):	1.0 OD x 1.31
Weight (lb.):	0.3

6.1.7.5 Slip Ring Assembly

A high reliability slip ring assembly of the type already being used in Shuttle Flight Deck instrumentation was selected for our experiment. It has coin silver rings, silver graphite brushes, and a rotor design which allows the leadwires to be exited through the shaft bore. It is a completely shielded unit meeting MIL-I-26600, and qualified per MIL-Q-9858 and MIL-C-45662A:

Manufacturer:	Airflyte Electronics Co.
Model:	Day-490
Part Number:	Day-490-10
Dimensions (in.):	4.00 O.D. X 4.88
Weight:	0.75

6.1.7.6 Housing

Manufacturer:	Rose Enclosures
Material:	Polycarbonate
Part Number:	33121609
Dimensions (in.):	6.29 x 4.72 x 3.54
Weight (lb.):	0.87

6.1.8 Control Module

Various controls and read-out instruments for the motor and warmers are installed in the hub of the spin apparatus (Figure 13). These include simple on-off switches, warmer selector switch and timer, rpm and watt-meter, and manual spin override. The control module also contains circuit breakers to protect against short circuits. Each item in the control module is defined below:

6.1.8.1 Warmer Selector Switch

This is a miniature printed circuit rotary selector switch used to select the desired heat pipe warmer for a particular test run. It is a totally enclosed explosion proof switch meeting the requirements of MIL-S-3786 and 22710.

Manufacturer:	Janco
Part Number:	EA45-AA-5SP
Current Rating:	3 Amps continuous
Dimensions (in.):	0.95 O.D. X 1.11
Weight (lb.):	0.07

6.1.8.2 Display Selector Switch

The display selector switch is a rotary switch identical to the one described in Section 6.1.8.1 above, except the Part No. is EA45-AA-3SP. It is used to switch between the tachometer and warmer Wattage readout.

6.1.8.3 Motor Speed Control

This is an 8 position push-button rotary type switch used to increase or decrease the speed or rpm of the motor in step increments from 0 to 160 rpm. It is an EMI shielded, sealed explosion proof switch meeting the requirements of MIL-S-22710/18:

Manufacturer:	Janco
Part Number:	D45BA-2ALCSP
Current Rating:	3 Amps continuous
Dimensions (in.):	1.70 X 1.25 X 0.50
Weight (lb.):	0.07

6.1.8.4 RPM/Wattage Read-out

A set of LEDs is used to display the motor rpm from a signal from the Servo Amplifier (6.1.7.3), and power supplied to the heat pipe warmers (6.1.2). The display selector switch, described in Section 6.1.8.2 above, is used to switch between RPMs and warmer Wattage readout.

Manufacturer:	General Instrument, Electric Switches Inc.
Type:	LED Numeric Displays
Part Number:	CMN6710
Range (RPM):	0 to 500
Range (Watts):	0 to 60
Dimensions (in.):	TBD
Weight (lb.):	0.06

6.1.8.5 Warmer Timer

This control allows a crew member to manually pre-set the time for a particular thermal performance test run, and provides a read-out of elapsed time. It has a maximum cycle time of 1 hour:

Manufacturer:	Deltrol,Electric Switches Inc.
Model:	116D-1
Part Number:	46436-81
Current Rating:	20 Amps
Dimensions (in.):	3.13 X 2.56 X 1.75
Weight (lb.):	0.15

6.1.8.6 Circuit Breaker

This is a single pole overcurrent circuit breaker. It will be installed in the primary electrical circuit between the 28V DC Orbiter power supply and the control module.

Manufacturer:	E-T-A, Electric Switches Inc.
Type:	Series Trip
Part Number:	44-100-P10
Rated Amps:	0.05 thru 5 Amps
Dimensions (in.):	1.67 X 0.75 X 0.43
Weight (lb.):	0.03

6.1.8.7 Housing

Manufacturer:	Rose Enclosures
Material:	Polycarbonate
Part Number:	33121211
Dimensions (in.):	4.8 X 4.72 X 4.13
Weight (lb.):	0.77

6.1.9 Brushless DC Fan

A fan is required to provide forced air cooling to the heat pipe condenser surfaces during the thermal performance test. Forced air cooling allows the heat pipes to be tested at power levels of practical interest. It was determined from ground testing (Section 5.1.2) that a power input of 40 Watts could be achieved at a heat pipe operating temperature of 55 |C with a fan of the type specified below.

Manufacturer:	Comair Rotron
Type:	Sprint^R Tubeaxial
Model No.:	ST24A3
Part Number:	032127
Rated Volts (VDC):	18-28
Run Current (mA):	140
Dimensions (in.):	3.15 x 3.15 x 1.26
Weight (lb.):	0.39

6.1.10 Safety Shroud

A safety shroud made of a transparent plastic or wire screen material will protect objects and crew members from colliding with the thermal performance apparatus while it is rotating. It will be designed to prevent physical injury and temperature contact during the thermal performance experiment. The shroud will be made of a thin flexible material so that it can be folded or collapsed for storage in the middeck locker.

Manufacturer:	Hughes/Design Models Inc.
Material:	TBD
Part Number:	TBD
Dimensions (in.):	TBD
Weight (lb.):	3.0 (Est.)

6.1.11 Video Cam/Corder

This off-the-shelf commercial grade 8mm video cassette camera recorder is a close derivative of hardware that has already flown. It can be mounted on a fixed attachment in the middeck area or it can be hand held by a crew member. It will be used to video tape the color changes of liquid crystals in response to changes in temperature of the heat pipe surfaces during thermal testing, and recording data from various digital read-outs described above. Data will be recorded both visually and on the sound track of the tape using the microphone. The battery pack will be fused per NASA JSC Letter ER-87-326. Specifications for the cam/corder are:

Manufacturer:	Sony
Type:	Compact one-piece camera recorder
Model:	CCD-M8U Handycam
Video Tape:	8mm, 2 hours
Battery Pack:	Special, fused
Microphone:	Included
Dimensions (in.):	TBD
Weight (lb.):	3.0 (with batteries)

6.1.11.1 DC Power Supply

Manufacturer:	TBD
Model:	TBD
Dimensions (in.):	TBD
Weight:	1.0

6.1.11.2 Velcro Attach Fixture

A fixture will be provided to Velcro the camera to a wall or floor of the middeck area. It will allow angular adjustments for aiming the camera. The astronaut has the option to hand hold the camera or attach it to the fixture:

Manufacturer:	Hughes/Design Models Inc.
Materials:	Aluminum/Velcro
Part Number:	TBD
Dimensions (in.):	TBD
Weight (lb.):	0.3 (Est.)

6.1.12 Video Light

Manufacturer:	Sony
Model:	TBD
Type:	TBD
Voltage:	TBD
Watts:	40
Dimensions (in.):	TBD
Weight (lb.):	0.3

6.1.12.1 Power Cable to Power Supply

The power cable from the Orbiter 28 VDC bus to the experimental apparatus will be supplied by NASA. However, Hughes will provide a connector in the base of the motor module housing (Section 6.1.7). of the thermal performance test apparatus, which will mate with a connector on the power cable. There will be only one power cable to supply electric power from the Orbiter bus to the apparatus.

6.1.12.2 Velcro Attach Bracket

The video light can be "Velcroed" to the middeck wall during video taping of the experiment.

Manufacturer:	Hughes/Design Models Inc.
Materials:	Aluminum/Velcro
Part Number:	TBD
Dimensions (in.):	TBD
Weight (lb.):	0.2 (Est.)

6.2 NUTATION DIVERGENCE APPARATUS

A layout drawing of the experimental apparatus for in-space nutation divergence testing is shown in Figure 23. Figure 24 is an isometric drawing of the apparatus. The hardware required to produce this apparatus is listed in Table 5.

6.2.1 Heat Pipes with Attach Brackets

These are the same heat pipes as described in Section 6.1.1.

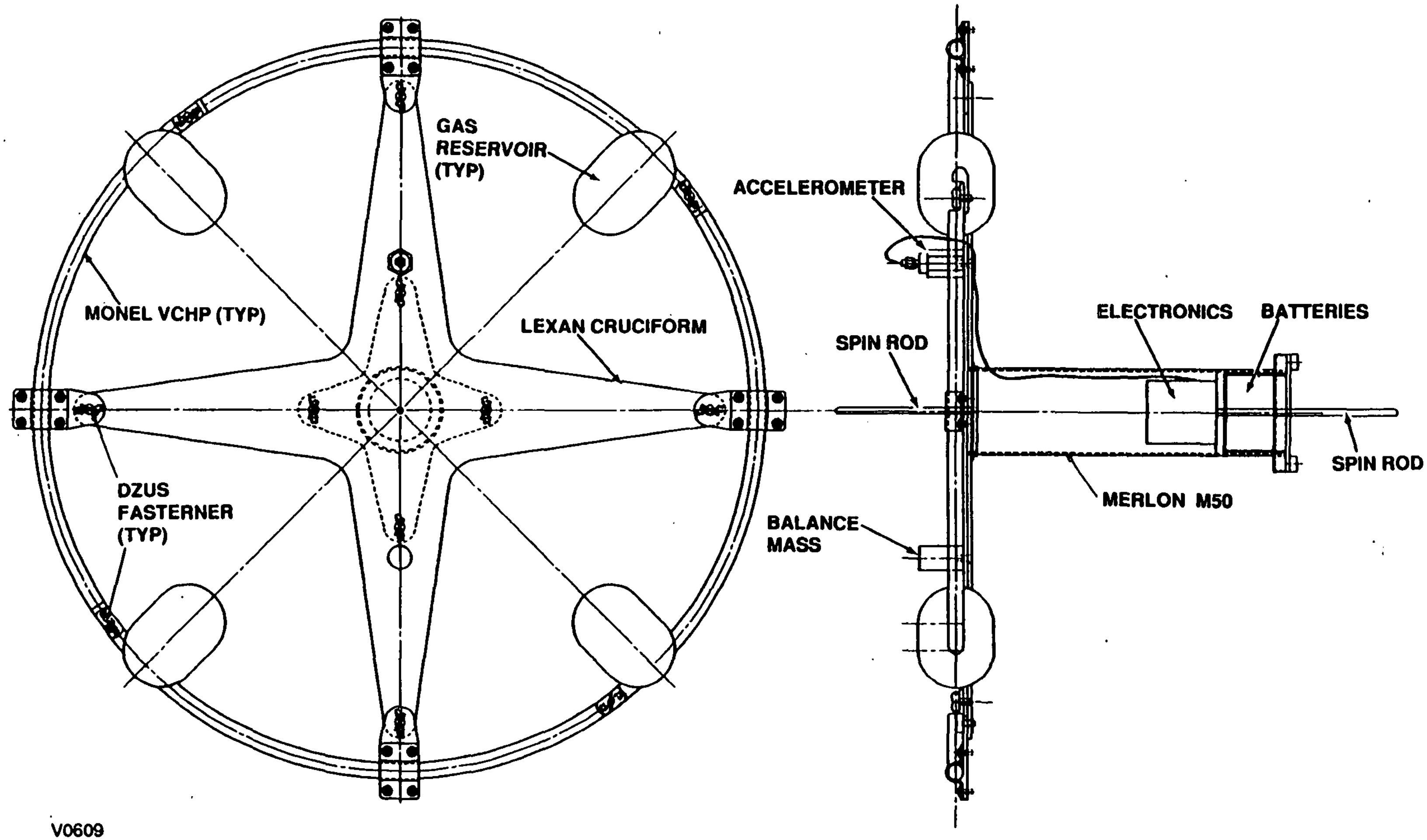

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Figure 23 Nutation divergence apparatus layout drawing.

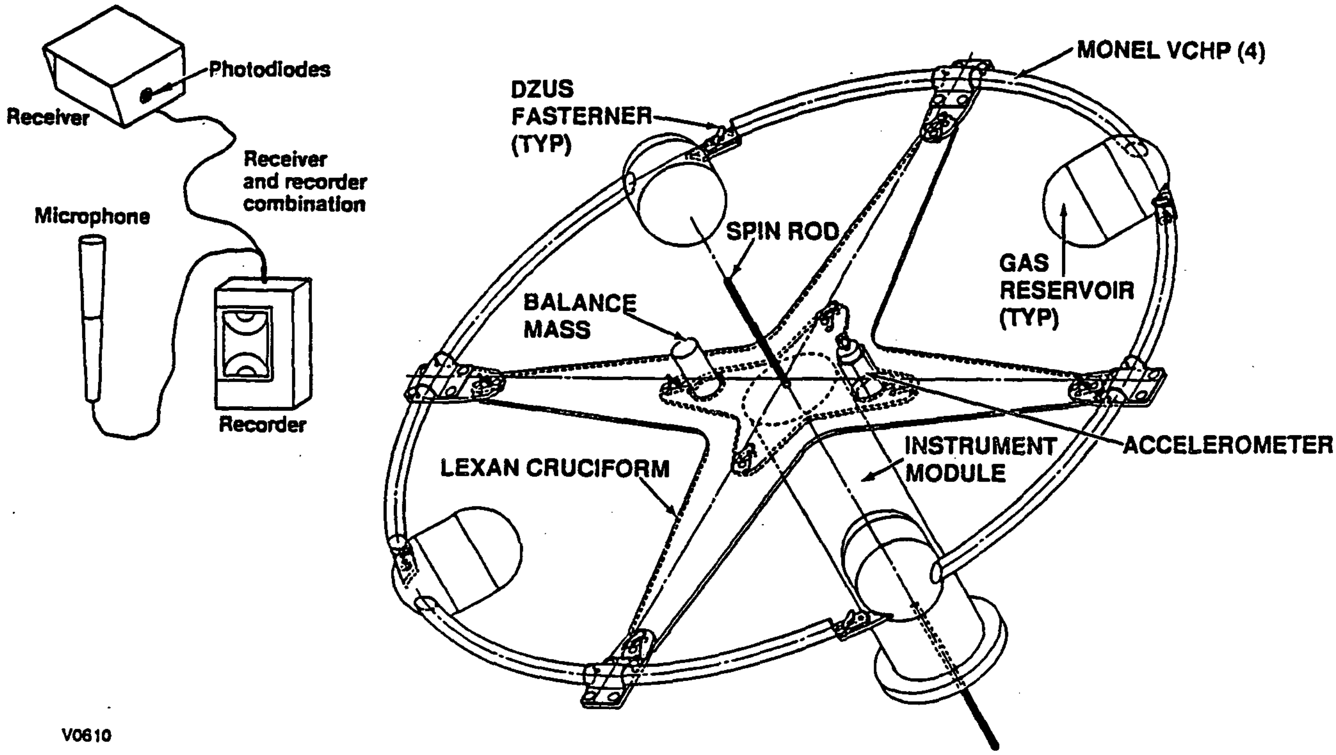

Figure 24 Nutation divergence apparatus design.

TABLE 5

LIST OF HARDWARE FOR
NUTATION DIVERGENCE EXPERIMENT

REF.	DESCRIPTION	QTY.	TOTAL WEIGHT (LB.)	POWER (WATTS)
6.2.1	Constant Conductance Heat Pipes (CCHPS) with Attach Brackets	8[1]	2.5	N/A
6.2.1	Variable Conductance Heat Pipes (VCHPs) with Attach Brackets	8[1]	6.7	N/A
6.2.2	Accelerometer	1	0.1	
6.2.3	Inertia Change Masses	8	2.0	N/A
6.2.4	Cruciform Support with Attachments	1[1]	1.0	N/A
6.2.5	Instrument Module			
6.2.5.1	Housing	1	0.3	N/A
6.2.5.2	Transmitter with Gain Control	1	1.1	N/A
6.2.5.3	Battery Pack	1 (2)[2]	0.6	N/A
6.2.5.4	Infrared Light Emitting Diodes (LEDs)	8	0.1	N/A
6.2.5.5	Battery Monitor	1	0.02	N/A
6.2.5.6	Power Switch	1	0.02	N/A
6.2.5.7	Spin Rods and Spin-up Cord	1	0.03	N/A
6.2.6	Cordless Screwdriver	1 (1)	3.0	N/A
6.2.7	Receiver Module			
6.2.7.1	Photodiodes	4	0.05	N/A
6.2.7.2	Batteries (9 V)	2 (2)	0.44	N/A
6.2.7.3	Power Switch	1	0.01	N/A
6.2.7.4	Level Indicator	1	0.02	N/A
6.2.7.5	Data Output Line (To Recorder)	1	0.05	N/A
6.2.7.6	Velcro Attach Bracket	1	0.25	N/A

TABLE 5 (Cont.)

REF. DESCRIPTION	QTY.	TOTAL WEIGHT (LB.)	POWER (WATTS)
6.2.8 Data Recorder	1	1.4	
6.2.8 Recording Tape	1 (2)	0.27	N/A
6.2.8 Batteries (1.5 V AA)	4 (4)	0.35	N/A
6.2.8 Microphone	1	0.1	N/A
6.2.9 Optical Tachometer	1	1.0	N/A
6.2.9 Batteries (1.5V AA Size)	4 (4)	0.35	N/A
6.2.10 Video Cam/Corder	1 (1)[1]	2.5	N/A
6.2.10 Video Tape (8mm Video Cassette)	1 (2)[1]	0.3	N/A
6.2.10 Battery Pack (Special)	1 (2)[1]	1.5	N/A
6.2.10.1 DC Power Supply	1[1]	1.0	15
6.2.10.2 Velcro Attach Fixture	1[1]	0.3	N/A
6.2.11 Video Light	1[1]	0.3	40
6.2.11.1 Power Cord to Power Supply	1[1]	0.1	N/A
6.2.11.2 Velcro Attach Bracket	1[1]	0.2	N/A
TOTAL		27.96[3]	55

NOTES:

1. This item used for both thermal performance and nutation divergence experiments.
2. Numbers on parentheses indicate number of flight spares.
3. This is the total weight of all items for the thermal performance test; see Table 6 for the combined weight of items for both the thermal performance and nutation divergence experiments.

6.2.2 Accelerometer

The accelerometer is mounted on the instrument module outboard of the model spin axis with its sensitive axis parallel to the spin axis.

Manufacturer:	PCB
Type:	Piezoelectric
Part Number:	TBD
Dimensions (in.):	TBD
Weight (lb.):	0.1 (Est.)

6.2.3 Inertia Change Masses

These removable masses will be attached to the instrument module and cruciform support to change the model inertia as required for various test runs. A single mass identical to the accelerometer is mounted to balance its effect on the mass properties.

Manufacturer:	Hughes/Design Models Inc.
Material:	Aluminum or Lexan
Part Number:	TBD
Dimensions (in.):	TBD
Weight (lb.):	0.25 Each (Est.)

6.2.4 Cruciform Support with Attachments

This structural member (the same as described in Section 6.1.5) is used to attach the heat pipe hoop assembly to the instrument module. It includes provisions for attaching inertia change masses.

Manufacturer:	Hughes/Design Models inc.
Material:	Aluminum or Lexan
Part Number:	TBD
Dimensions (in.):	TBD
Weight (lb.):	1.0

6.2.5 Instrument Module

This module will house the transmitter which sends the nutational accelerometer signal to the receiver using infrared LEDs. It includes provisions for attaching the cruciform support, the accelerometer, and inertia change masses.

6.2.5.1 Housing

Manufacturer:	Hughes/Design Models inc.
Material:	Polycarbonate
Part Number:	TBD
Dimensions:	TBD
Weight, Empty (lb.):	0.3 (Est.)

6.2.5.2 Transmitter with Gain Control

This control will change the amplitude of the accelerometer signal.

Manufacturer:	Hughes/Applied Dynamics Laboratory
Type:	TBD
Part Number:	TBD
Dimensions (in.):	TBD
Weight (lb.):	1.1 (Est.)

6.2.5.3 Battery Pack

This replaceable battery pack contained in the instrument module consists of a shell made of polycarbonate material surrounding twelve (12) AA batteries with welded connectors. It is fused to prevent shorting, per NASA JSC letter ER-87-326.

Manufacturer:	Hughes/Applied Dynamics Laboratory/Design Models Inc.
Type:	TBD, fused.
Part Number:	TBD
Dimensions (in.):	TBD
Weight (lb.):	0.6 Total

6.2.5.4 Infrared Light Emitting Diodes (LEDs)

Manufacturer:	TBD
Type:	TBD
Part Number:	TBD
Dimensions (in.):	TBD
Weight (lb.):	0.1 Total

6.2.5.5 Battery Monitor

Permits battery voltage checks as required.

Manufacturer:	TBD
Type:	TBD
Part Number:	TBD
Dimensions (in.):	TBD
Weight (lb.):	0.02 (Est.)

6.2.5.6 Power Switch

Manufacturer: TBD
Type: TBD
Part Number: TBD
Dimensions (in.): TBD
Weight (lb.): 0.01 (Est.)

6.2.5.7 Spin Rods and Spin-Up Cord

Two (2) aluminum rods with knurled tips will screw into the ends of the model, permitting it to be restrained from translational motion during spin-up. The spin-up cord will be attached to the instrument module with Velcro, and then wrapped around it several times. Pulling this cord while restraining the spin rods will cause the model to spin up.

Manufacturer: Hughes/Design Models Inc.
Material: 6061-T6 Aluminum
Part Number: TBD
Dimensions (in.): TBD
Weight (lb.): 0.015 Each (Est.)

6.2.6 Cordless Screwdriver

As result of the KC-135 Flight Test described in Section 5.2 of this report, it was concluded that a cordless screwdriver, or the equivalent, is the most effective method for spinning-up and releasing the test apparatus in a low gravity environment. Therefore, the spin-up cord described above (6.2.5.7) will serve as a backup method in the event of any unforeseen problems with the cordless screwdriver in flight.

Manufacturer: SKIL®
Material: Misc.
Part Number: TBD
Dimensions (in.): TBD
Weight (lb.): 1.5 Each (Est.)

6.2.7 Receiver Module

This module receives the infrared signal containing the nutational accelerometer data and relays it to the data recorder. It also contains audio and visual signal level monitors.

6.2.7.1 Photodiodes

Manufacturer:	TBD
Part Number:	TBD
Quantity:	4
Dimensions (in.):	TBD
Weight (lb.):	0.0125 Each (Est.)

6.2.7.2 Batteries

Batteries will be fused per NASA JSC letter ER-87-326.

Manufacturer:	Duracell
Type:	9 V
Part Number:	TBD
Quantity:	2
Dimensions (in.):	TBD
Weight (lb.):	0.11

6.2.7.3 Power Switch

Manufacturer:	TBD
Type:	TBD
Part Number:	TBD
Dimensions (in.):	TBD
Weight (lb.):	0.01 (Est.)

6.2.7.4 Level Indicator

Contains ten (10) LEDs for signal level indication.

Manufacturer:	Hughes/Applied Dynamics Lab
Type:	TBD
Part Number:	TBD
Dimensions (in.):	TBD
Weight (lb.):	0.02 (Est.)

6.2.7.5 Data Output Line

Cable connecting Receiver Module to Data Recorder.

Manufacturer:	TBD
Type:	TBD
Part Number:	TBD
Dimensions (in.):	TBD
Weight (lb.):	0.05 (Est.)

6.2.7.6 Velcro Attach Bracket

The Receiver Module can be "Velcroed" to the middeck wall or floor during the experiment.

Manufacturer:	Hughes/Design Models Inc.
Material:	Aluminum/Velcro
Part Number:	TBD
Dimensions (in.):	TBD
Weight (lb.):	0.25 (Est.)

6.2.8 Data Recorder

This device records the nutational accelerometer data on a standard audio cassette. It also records verbal notes on each experimental run. Batteries will be fused.

Manufacturer:	TBD
Model:	TBD
Type:	TBD
Recording Tape:	TBD
Batteries:	Two (2) 1.5 V AA
Microphone:	TBD
Dimensions (in.):	TBD
Weight (lb.):	0.7 With batteries and tape (Est.)

6.2.9 Optical Tachometer

This photoelectric device uses a reflected beam of light to determine the spin speed in RPM of the free flying model.

Manufacturer:	Cole-Parmer
Catalog Number:	R-8204-00
Batteries:	Four (4) AA, fused.
Dimensions (in.):	6.25 X 2.5 X 1.25
Weight (lb.):	1.0

6.2.10 Video Cam/Corder

The cam/corder described in Section 6.1.11 will also be used to record the Nutation Divergence model behavior and the experimental procedures. It will also be used as a back-up for the optical tachometer to record spin speed.

Manufacturer:	SONY
Type:	Compact one-piece camera recorder
Model:	CCD-M8U Handycam
Video Tape:	8mm, 2 hours.
Battery Pack:	Special, fused.
Dimensions (in.):	TBD
Weight (lb.):	3.0 (with batteries)

6.2.10.1 DC Power Supply

Manufacturer:	TBD
Model:	TBD
Dimensions (in.):	TBD
Weight (lb.):	1.0

6.2.10.2 Velcro Attach Fixture

A fixture will be provided to Velcro the camera to a wall or floor of the middeck area (Section 6.1.11.2).

6.2.11 Video Light

The video light will be used to improve the quality of the video data (Section 6.1.12).

6.2.11.1 Power Cord to Power Supply

This power cord is supplied with the video light.

6.2.11.2 Velcro Attach Bracket

As previously described (Section 6.1.12.2) the video light can be "Velcroed" to the middeck wall or floor during video taping of the experiment.

6.3 SUMMARY OF WEIGHT AND POWER

The weight and power requirements for this experiment are summarized in Table 6. Note that the weight column represents the **combined weight** for both the thermal performance and nutation divergence experiments. Since some of the components (e.g., heat pipes, cruciform, ...) are common to both experiments then the total weight in Table 6 is less than the sum of the weights given in Tables 3 and 5 for the individual experiments, respectively. However, the power requirement for the thermal performance experiment is independent of the power for the nutation divergence experiment, and the power requirement for each experiment is listed separately.

TABLE 6

SUMMARY OF WEIGHT AND POWER REQUIREMENTS

ITEM	QTY.	TOTAL WEIGHT (LB.)	POWER (WATTS)	
			THERMAL PERFORMANCE	NUTATION DIVERGENCE
Heat Pipes, Warmers, and Thermostats	16*	10.1	< 40	
Cruciform Support	1*	1.0		
Adapter Plate	1	6.5		
Motor Module	1	2.9	17.1	
Control Module	1	1.2	< 1.0	
Brushless DC Fan	1	0.4	3.3	
Safety Shroud	1	3.0		
Accelerometer and Inertia Masses	1	2.1		
Instrument Module	1	1.6		
Cordless Screwdriver	2	3.0		
Receiver Module and Bracket	1	0.4		
Data Recorder and Tapes	1*	1.8		
Optical Tachometer	1	1.0		
Video Cam/Corder, Tapes, and Bracket	2*	8.2	15**	15**
Video Light and Bracket ***	1*	0.6	40	40
Batteries	Lot*	3.2		
TOTAL	---	47.0	< 116.4	55

* These items used for both thermal performance and nutation divergence experiments.
** Cam/Corder can operate on batteries.
*** The video light and bracket are optional.

7.0 FLIGHT TEST PLANS

7.1 THERMAL PERFORMANCE TESTS

7.1.1 Test Setup

Once the shuttle achieves orbit, and a micro-gravity environment has been established, the items listed in Table 3 will be removed from the middeck stowage locker and assembled as follows: A crewmember will attach the Adapter Plate (6.1.6) to the frame of the middeck lockers using quick release fasteners. The location of the plate on the rack of lockers shall be based on the following clearance requirements. A minimum radius of 2.0 ft. is required from the center of the Adapter Plate, in the plane of the Adapter Plate, for clearance of the rotating heat pipes. This clearance zone shall extend a minimum of 3.0 ft. in a direction perpendicular to the Adapter Plate for video taping purposes. In summary, a 4.0 ft. diameter x 3.0 ft. length cylindrical clearance zone, centered on the Adapter Plate, is required for this experiment.

After the Adapter Plate is mounted on the lockers, the Motor Module (6.1.7) will be attached to the Adapter Plate with quick release fasteners as illustrated in Figure 21. The plate will already have fittings attached for ease of assembly.

Next the Lexan^{R} Cruciform Support (6.1.5) is inserted over the drive shaft of the motor module. Then the Control Module (6.1.8) plugs into the hub of the assembly (Figure 21), making the appropriate electrical connections, and is locked in place with quick release fasteners to hold the entire assembly together.

Four Heat Pipes (6.1.1) will be attached radially to the Cruciform Support as shown in Figure 21 using the quick release fasteners already attached to the Heat Pipes. Care must be taken to select specific heat pipes with the appropriate liquid fill inside for each experiment. The heat pipes are identified accordingly and specific configurations are defined in the test procedures below. Finally, the clear plastic Safety Shroud (6.1.10) is assembled over the apparatus and the Video Cam/Corder (6.1.11) is mounted in the opening at the center of the shroud. The power cords for the DC motor and electrical warmers shall be plugged into the 28 V DC middeck ceiling or floor outlets last.

7.1.2 Static Performance Test Procedure

Prior to spinning the heat pipes, a static performance test will be performed without rotating the apparatus to compare the maximum heat transport capacity in a micro-gravity environment with performance measured on the ground. For this experiment either four FCHPs or four VCHPs shall be attached to the Cruciform Support as described in Section 7.1.1 above. Each heat pipe shall have a unique fill fraction. The various test configura-

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tions for each run are summarized in Table 7.

With the Warmer Selector Switch (6.1.8.1) set to Heat Pipe No. 1, and the motor switch turned off, adjust the warmer electrical power supply to 80% of the maximum power obtained in ground testing. Record the startup transient with the Video Cam/Corder (6.1.11). After one-half hour, when steady state temperatures have been reached, increase the power in 10-watt increments at fifteen minute intervals until **dryout** is observed. Record the colors of the liquid crystals at each power level, just prior to increasing power, with the Video Cam/Corder.

Dryout, for purposes of this experiment, is defined in two ways:

- Liquid crystal temperature sensors indicate that temperature gradient larger than 10 °C exists in the evaporator region.
- Thermostat shuts off power when maximum evaporator temperature is reached.

The test will be concluded if either one of these criteria are met. The test will also be stopped if the maximum power available for the warmers is reached before either of these conditions are obtained.

The above sequence will be repeated for Heat Pipe Nos. 2 through 4.

7.1.3 <u>Spin Test Procedure</u>

After completion of the static testing described in Section 7.1.2 above, the maximum heat transport capacity will be measured for various acceleration levels between 0 and 1-g. These accelerations will be achieved by rotating the heat pipes at various rpm.

Allow the Heat Pipes to return to ambient temperature before proceeding. The various test runs for the dynamic performance test are summarized in Table 7.

With the Warmer Selector Switch (6.1.8.1) set to Heat Pipe No. 1, adjust the warmer power supply to one-half the maximum value obtained in the static testing. After fifteen minutes, when steady state temperatures have been reached, turn on the Motor Speed Control (6.1.8.3) and adjust the speed to 20 rpm. Record the startup transient with the Video Cam/Corder (6.1.11). After fifteen minutes record the appearance of the liquid crystals on video tape, and increase the speed of rotation in 4 rpm increments, at fifteen minute intervals. Continue to increase rotation until a speed of 20 rpm or **dryout** is observed, whichever occurs first. Record the colors of the liquid crystals

TABLE 7

SUMMARY OF IN-SPACE THERMAL PERFORMANCE TEST PLAN

RUN NO.	HEAT PIPE CONFIG.	LIQUID FILL FRACTION (%)	PRIORITY	DURATION (MINUTES)	ELAPSED TIME (HOURS)	COMMENTS
1.1	FCHP	90	1B	30	0.5	Static performance test at 40 Watts and 0 RPM. No dryout expected.
1.2	FCHP	100	1A	30	1.0	
1.3	FCHP	110	1B	30	1.5	
1.4	FCHP	120	1A	30	2.0	
2.1	FCHP	90	1B	90	3.5	Spin performance test; start at 40 Watts and 4 RPM. Increase spin speed in 4 RPM steps until dryout.
2.2	FCHP	100	1A	90	5.0	
2.3	FCHP	110	1B	90	6.5	
2.4	FCHP	120	1A	90	8.0	
3.1	FCHP	90	2A	15	8.3	Rewicking test. Record time for wick to reprime after spinning at 100 RPM.
3.2	FCHP	100	2A	15	8.5	
3.3	FCHP	110	2A	15	8.8	
3.4	FCHP	120	2A	15	9.0	
4.1	VCHP	90	2A	15	9.3	Rewicking test. Record time for wick to reprime after spinning at 100 RPM.
4.2	VCHP	100	2A	15	9.5	
4.3	VCHP	110	2A	15	9.8	
4.4	VCHP	120	2A	15	10.0	
5.1	VCHP	90	3B	60	11.0	Static performance test. Start at 20 watts and 0 RPM. Increase power in 10 Watt steps until dryout.
5.2	VCHP	100	3A	60	12.0	
5.3	VCHP	110	3B	60	13.0	
5.4	VCHP	120	3A	60	14.0	
6.1	VCHP	90	3B	75	15.3	Spin performance test; start at 20 Watts and 10 RPM. Increase spin speed in 10 RPM steps until dryout.
6.2	VCHP	100	3A	75	16.5	
6.3	VCHP	110	3B	75	17.8	
6.4	VCHP	120	3A	75	19.0	

at each step in rpm at steady state conditions just prior to increasing the speed of rotation, and during acceleration to the next higher level. **Dryout** will be defined as before in Section 7.1.1 for static performance testing. Heat Pipe warmer power and motor speed will be returned to zero after the completion of each heat pipe test.

The above sequence will be repeated for Heat Pipe Nos. 2 through 4 (Table 7).

7.1.4 Rewicking Test

Four VCHPs (6.1.1) will be attached to the Cruciform Support (6.1.5) as described in Section 7.1.1 above. Each VCHP will have a different fill fraction.

This test will involve spinning the assembly of four VCHPs up to 100 rpm to force the working fluid into the reservoirs. Next, the assembly will be brought to rest, and the evaporator portion of one VCHP will be warmed briefly for about five minutes with the Warmer Selector Switch (6.1.8.1) set to Heat Pipe No. 1. Temperature sensitive liquid crystals bonded to the heat pipe surface will indicate whether the heat pipe has recovered. If recovery has not yet occurred, heat pipe **dryout** will be observed (see Section 7.1.2), and the electrical warmer power will be turned off. Then the switch will be set to Heat Pipe No. 2, which will be warmed in the evaporator region and similarly observed for dryout. In this way, the recovery time will be determined. If dryout does not occur, then the heat pipe should be operated for one-half hour, minimum, until steady state conditions are reached. All results and observations should be recorded with the Video Cam/Corder (6.1.11). The rewicking test will then be repeated for the FCHPs as listed in Table 7.

This test will be conducted both on the ground with the plane of rotation parallel to the ground, and in orbit. Correlation of ground and in-space data will permit prediction of wicking times for future heat pipe designs.

7.2 NUTATION DIVERGENCE TEST

7.2.1 Test Setup

When a micro-gravity environment has been established in orbit, the items listed in Table 4 will be removed from the mid-deck stowage locker and assembled as shown in Figure 23. The Lexan[R] Instrument Module (6.2.5) attaches to the Cruciform Structure (6.2.4) with quick-release fasteners. Four Heat Pipes (6.2.1) attach circumferentially to the Cruciform Support (6.2.4) as shown in Figure 23 using quick release fasteners already attached to the Heat Pipes. Care must be taken to select specific Heat Pipes with the appropriate liquid fill inside for each

experiment. The Heat Pipes are identified accordingly and specific configurations are called out in the test procedures below for each particular test.

Finally, the Receiver Module (6.2.7), Data Recorder (6.2.8), Optical Tachometer (6.2.9), Video Cam/Corder (6.2.10) and Video Light (6.2.11) are stationed and aligned at various locations in the middeck area using Velcro or other convenient means of attachment.

7.2.2 Nutation Divergence Test Procedure

A minimum of four test configurations are planned for this experiment. In each experiment either four FCHPs with two different fill fractions or four VCHPs with two different fill fractions will be assembled in a hoop on the Lexan[R] Cruciform Support (6.2.4) as described in Section 7.2.1 above. The two heat pipes with identical fill fractions shall be mounted diametrically opposed to each other for balance.

Two crew members are required to perform this experiment. One will spin up the model with the Cordless Screwdriver (6.2.6), or the equivalent, while the other crew member measures spin speed. Crew member No. 1 can record the results on video tape, and then retrieve the model.

As previously discussed, the accelerometer signals from the LEDs (6.2.5.4) are detected and recorded by a photosensitive Receiver Module (6.2.7) wired to a stereo cassette tape Data Recorder (6.2.8). One recorder channel is used for data, while a second is used to record commentary using the attached microphone. The receiver and recorder attach to the middeck floor or lockers with velcro. Spin speed of the heat pipe assembly will be measured with an optical tachometer and will also be recorded verbally on the data tape.

After completion of the first run, the Heat Pipe configuration will be changed and the process is repeated. The various Nutation Divergence test runs are summarized in Table 8.

TABLE 8

SUMMARY OF IN-SPACE NUTATION DIVERGENCE TEST PLAN

RUN NO.	HEAT PIPE TYPE	LIQUID FILL (%)*	NO. OF HEAT PIPES	DURATION (MINUTES)	ELAPSED TIME (HOURS)	COMMENTS
7.1	VCHP VCHP	90 100	2 2	10	0.2	Measure VCHP time constant; one hoop.
7.2	VCHP VCHP	110 120	2 2	10	0.3	Effect of fill fraction; one hoop.
7.3	VCHP VCHP VCHP VCHP	90 100 110 120	2 2 2 2	15	0.6	Effect of combined time constant; two VCHP hoops.
7.4	FCHP FCHP	90 100	2 2	10	0.8	Measure FCHP time constant; one hoop.
7.5	FCHP FCHP	110 120	2 2	10	0.9	Effect of fill fraction; one hoop.
7.6	FCHP FCHP FCHP FCHP	90 100 110 120	2 2 2 2	15	1.2	Effect of combined time constant; two FCHP hoops.
8.1	VCHP VCHP	90 100	2 2	15	1.4	Change cg/inertia from Run #7.1.
8.2	VCHP VCHP	110 120	2 2	15	1.7	Change cg/inertia from Run #7.2.
8.3	FCHP FCHP	90 100	2 2	15	1.9	Change cg/inertia from Run #7.4.
8.4	FCHP FCHP	110 120	2 2	15	2.2	Change cg/inertia from Run #7.5.
9.1	VCHP VCHP	90 100	2 2	10	2.3	Change spin speed from Run #7.1.
9.2	VCHP VCHP	110 120	2 2	10	2.5	Change spin speed from Run #7.2.
9.3	FCHP FCHP	90 100	2 2	10	2.7	Change spin speed from Run #7.4.
9.4	FCHP FCHP	110 120	2 2	10	2.8	Change spin speed from Run #7.5.

* The two heat pipes with identical fill fractions shall be mounted diametrically opposite each other.

8.0 SUMMARY

Our primary objective, then, is to obtain flight data for making design improvements in space heat pipes, and to make recommendations for upgrading the analytical models. The results will facilitate interpretation of VCHP and FCHP ground test data when making predictions for the thermal performance of heat pipes in space.

Both thermal performance and nutation divergence (fluid sloshing) type experiments are planned. Nutation divergence results will be applied to the analytical modeling of nutation induced by the motion of heat pipe working fluid, permitting design improvements which minimize the interference of heat pipes with spacecraft dynamics. Information gained regarding performance under acceleration and excess working fluid effects will be used to improve design methods, resulting in lighter weight, higher reliability, and more efficient spacecraft thermal systems. These experiments will also improve our understanding of heat pipe start-up, and repriming of wicks in space.

The Phase B accomplishments are summarized as follows:

- Confirmed location of the experiment in the middeck area--as proposed.
- Estimated electrical power, weight, and stowage requirements.
- Significant results of hardware evaluation task are:
  - Determined heat pipe thermal requirements and spin rpms for the flight experiment.
  - Determined that a fan will be required to achieve realistic power levels and a degree of temperature control.
  - Determined that a safety shroud will be required for the thermal performance experiment.
  - Verified feasibility of thermochromic liquid crystals (TLCs) for temperature measurement; selected bonding technique.
- Performed KC-135 flight tests with nutation divergence mockup apparatus:
  - Verified spin-up, release, and capture technique.
  - Selected battery powered screwdrever, or equivalent, as spin-up device.

- Data acquisition and photographic recording methods demonstrated for similar experiment apparatus during previous program.

- R. N. Stuckey of NASA JSC was assigned as Payload Integration Manager (PIM).

- Pre-Phase 0 safety review completed.

To minimize complexity and cost, as well as to improve manifesting flexibility, these experiments are planned for the middeck area of the crew compartment. An overriding theme of our experiment is to "keep it simple".

The requirement for crew training and support of this experiment has been recognized by NASA and must be considered during the manifesting process. The thermal performance experiment can be conducted as time permits and does not require each test to run consecutively. Also, the experiment can be constructed so that it can be rotated out of the way of other middeck lockers and will only block the lockers devoted to the heat pipe experiment.

Safety issues are reviewed in greater detail in the Phase B safety report*. However, it should be noted here that a safety shroud will be designed in Phase C/D to prevent physical injury from the thermal performance apparatus as well as temperature contact. The maximum temperature of the heat pipes is only 65 °C, but this exceeds the unshielded maximum temperature of 45 °C for middeck experiments by 20 °C. When the heaters are turned off the experiment should quickly cool to a safe temperature, because of low thermal mass, to permit a contingency restow. An analysis and testing shall be performed during Phase C/D to determine the actual cool down time. A possible air lock location for the thermal performance experiment is also being considered by NASA.

Prototypes of the spinning nutation divergence experiment were tested on a KC-135 flight and no significant hazards or problems were encountered. Indeed, the device is stopped by catching it with one's hands.

EMI testing is planned for Phase C/D as well as pressure testing on the heat pipes. The heat pipes are charged with water and have a minimum factor of safety of 8.5, with a maximum pressure of only 3.7 psia at 65 °C. Structural analysis and testing will be performed on the test apparatus to insure that it will maintain its integrity during the spin-up. However, formal qualification tests are not required for middeck experiments.

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* Smith, M. O., "Contract Phase B NASA Pre-Phase 0 Safety Report", Hughes Space and Communications Group, December 1989.

The video equipment is a close derivative of hardware that has already flown. It will be qualified by similarity. Most of the batteries for the experiment are AA alkaline type, and use of orbiter power to run the video equipment is being considered.

In conclusion, the heat pipe experiment does have some unique concerns, but it is felt that there are no "show stoppers". Pre-Phase 0 safety meetings held at the NASA Johnson Space Center safety office and astronaut office were positive, and no serious difficulties were identified. The micro-gravity test flights on the KC-135 verified the feasibility of the nutation divergence experiment and showed that the spin-up and release can be performed relatively easily in a micro-gravity environment. Two additional KC-135 flights are planned in Phase C/D. Hughes previous experience with middeck payloads is also a significant asset to the project and should contribute to its successful completion.

APPENDIX

HEAT PIPE PERFORMANCE (HPP) EXPERIMENT

PHASE C/D EXPERIMENT PLAN

- LIST OF TASKS BY WBS
- STATEMENT OF WORK
- SCHEDULE
- FLOWCHART
- LIST OF MATERIALS AND COSTS (UNBURDENED)
- LABOR REQUIREMENTS
    - BY MONTH
    - BY WBS ELEMENT
    - BY LABOR CATEGORY

HEAT PIPE PERFORMANCE (HPP) EXPERIMENT

LIST OF TASKS BY WBS

WBS	TASK NAME
1.0	PROJECT MANAGEMENT
2.0	DETAIL DESIGN
3.0	PROCUREMENT
4.0	FABRICATION
5.0	GROUND TESTING
6.0	DELIVER HARDWARE
7.0	KC-135 FLIGHT TESTING
8.0	IN-SPACE EXPERIMENT
9.0	DOCUMENTATION
10.0	REVIEWS & MEETINGS

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1/25/90

STATEMENT OF WORK

FOR

HEAT PIPE PERFORMANCE (HPP) EXPERIMENT

PHASE C/D

Hughes Aircraft Company, Electron Dynamics Division and Space and Communications Group, will provide the personnel, facilities and material to perform Phase C/D of the flight experiment as outlined in the following Statement of Work. Phase C/D consists of experiment detail design, fabrication, ground test, and flight testing. A Gantt chart is attached to this Statement of Work to show relative timing and sequence of the various tasks.

WBS 1.0 PROJECT MANAGEMENT

Hughes will assign a Program Manager who will be directly responsible for the technical and administrative direction of the program. He will be the key interface with the NASA GSFC Technical Monitor. He will coordinate the activities of specific task leaders, and direct and fund the program team to meet the needs of the program. He will be responsible for all presentations documentation and technical reports.

WBS 2.0 DETAIL DESIGN

The detail design shall include verification of the proposed temperature instrumentation technique, analysis, safety evaluation, and a drawing package. The GSFC project manager must verify that the proposed temperature instrumentation will function before detail design is started. In addition to meeting flight test requirements, the hardware will be designed for stowage in two standard Middeck drawers.

2.1 Analysis

Fixed Conductance Heat Pipes (FCHPs) and Variable Conductance Heat Pipes (VCHPs) will be investigated. Both designs use triply distilled water as the working fluid. The VCHPs have a gas reservoir approximately 1.5 in. O.D. by 2.0 in. long attached to the condenser end, whereas the FCHPs do not. Both FCHPs and VCHPs will be fabricated of 0.5 in. O.D. monel tubing approximately 19.0 in long. The VCHP design uses a central core knitted copper mesh wick positioned in the heat pipe by spacer wicks, and the FCHP uses axial grooves. Mechanical, electrical, and thermal analysis shall be performed to support the Safety Evaluation in Task 2.2, component selec-

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tion, and to determine the final dimensions for the detailed drawings in Task 2.3. Heat pipe thermal performance and nutation divergence performance models shall be prepared based on analysis. The methodology of applying data from the nutation divergence experiment will be defined. Test results will be compared with the predicted performance and recommendations will be made for upgrading the models, if necessary.

2.2 Safety Evaluation

Analysis performed in Task 2.1 above will be used to verify that the heat pipes and experiment apparatus meet NASA "Safety Policy and Requirements" per NHB 1700.7B. All components and materials will be evaluated for compliance with NHB 8060.1, "Flammability, Odor, and Offgassing Requirements and Test Procedures for Materials in Environments that Support Combustion" and the requirements of SE-R-0006, "General Specification, NASA JSC Requirements for Materials and Processes" or an approved equivalent. Safety issues will be reviewed, and the Pre-Phase 0 Hazard Analysis will be updated as required. A safety shroud will be designed to prevent physical injury and temperature contact during the thermal performance experiment.

2.3 Drawings

Based on the analysis performed in Task 2.1 and the safety evaluation performed in Task 2.2 a formal Released Drawing Package will be prepared. The drawing package will include piece-part, sub-assembly, and final assembly drawings of the heat pipes, as well as the thermal performance and nutation divergence test apparatus, and safety shroud.

WBS 3.0 PROCUREMENT

Materials, machined parts, and components such as switches, motors, and slip ring assemblies shall be purchased in accordance with the quality requirements of MIL-Q-9858. Parts and materials will be subject to receiving inspection and materials analysis for compliance with the drawing requirements. Records will be maintained of parts usage in compliance with CPFF contractual requirements.

WBS 4.0 FABRICATION

The drawings produced in Task 2.3 above will be used for machining of piece-parts, procurement of components, and assembly of the heat pipes and test apparatus for the thermal performance and nutation divergence experiments. Fabrication of the heat pipes and test apparatus will be in accordance with the quality requirements of MIL-Q-9858.

4.1 Heat Pipe Fabrication

FCHPs will be fabricated of 0.5 in. O.D. monel tubing with axial grooves that are electrical-discharge machined directly into the tube wall material. End caps will be electron beam welded in place. The VCHPs are also fabricated of 0.5 in. O.D. monel tubing. However, the VCHPs have a knitted mesh copper wick positioned in the heat pipe by spacer wicks, and a gas reservoir at the condenser end. The tubing and reservoir parts will be electron beam welded in place, after installation of the wick. After welding, all of the heat pipes will be formed into the shape of a quarter circle to fit the test apparatus. Each heat pipe will have quick-release type fittings at the ends for attachment to each other and to the cruciform support structure (Task 4.2.1).

4.1.1 FCHPs: Twelve (12) FCHPs will be fabricated in accordance with the drawings produced in Task 2.3 above. There will be two (2) sets of four (4) heat pipes for the flight experiment and one (1) spare set of pipes. The heat pipes will be processed and sealed with four fill fractions of triply distilled water ranging from 90 to 120 percent of the calculated fill. Each pair of heat pipes will be processed with the same fill fraction of working fluid.

4.1.2 VCHPs: Twelve (12) VCHPs will be fabricated in accordance with the drawings produced in Task 2.3 above. There will be two (2) sets of four (4) heat pipes for the flight experiment and one (1) spare set of pipes. The heat pipes will be processed and sealed with four fill fractions of triply distilled water ranging from 90 to 120 percent of the calculated fill. Each pair of heat pipes will be processed with the same fill fraction of working fluid. Note that VCHPs will not have noncondensable gas inside them for these experiments.

4.2 Experiment Apparatus

Two (2) complete sets of experiment apparatus shall be fabricated, one (1) flight and one (1) spare. In addition to fabrication and assembly of the items described below, the experiment apparatus shall include purchased items such as: electrical warmers for the heat pipes, thermostats and temperature sensitive liquid crystal displays, video Cam/Corder, video light and brackets, accelerometers, and optical tachometer. Brackets will be provided to "Velcro" the video Cam/Corder, video light, and nutation divergence receiver module to a wall or floor of the Middeck area. NASA will provide a cable to plug into the middeck electrical power bus. The experiment apparatus will include an appropriate connector to mate with the NASA cable.

4.2.1 Cruciform Support: Two (2) cruciform supports will be fabricated in accordance with the drawings produced in Task 2.3. The cruciform support will be equipped with removable inertia masses for the nutation divergence experiment and quick-release fasteners for attachment of the heat pipes.

4.2.2 Instrument Module: Two (2) instrument modules will be fabricated in accordance with the drawings produced in Task 2.3. Each module shall contain the transmitter which sends the nutation accelerometer signal to the receiver using infrared LEDS. It will also include provisions for attaching the cruciform support, accelerometer, and inertia change masses.

4.2.3 Receiver/Recorder Module: Two (2) receiver/recorder modules will be assembled in accordance with drawings produced in Task 2.3. Each module shall contain audio and visual signal level monitors. They will record the nutation accelerometer data on a standard audio cassette.

4.2.4 Motor Module: Two (2) motor modules will be fabricated in accordance with the drawings produced in Task 2.3. The motor module contains a brushless DC motor for rotating the heat pipe assembly, a servo amplifier for controlling the motor, a gearhead, an override clutch for safety purposes, and a slip ring assembly. The motor module housing shall be made of a non-conductive material such as Lexan[R].

4.2.5 Control Module: Two (2) control modules will be fabricated in accordance with drawings produced in Task 2.3. The control module shall contain on-off switches, warmer selector switch and timer, rpm and watt-meter indicators, and manual spin override. The control module shall also contain approved circuit breakers to protect against short circuits.

4.2.6 Safety Shroud: Two (2) safety shrouds will be fabricated in accordance with drawings produced in Task 2.3. The shroud will be made so that it can be folded or collapsed for storage in a Middeck drawer.

4.2.7 Adapter Plate: Two (2) adapter plates will be fabricated in accordance with drawings produced in Task 2.3. The adapter plate is required for mounting the thermal performance test apparatus to the rack of middeck lockers during operation of the test, and shall be machined out of aluminum plate material. It also acts as a heat spreader plate for the electric motor.

WBS 5.0 GROUND TESTING

The test procedures developed in Task 9.5.1 will be used to check out the flight test apparatus, and to verify that the various mechanisms, controls, data acquisition techniques, and safety measures work properly. Ground testing will consist of Thermal Performance, Nutation Divergence, and Safety Tests.

5.1 Thermal Performance

Each deliverable heat pipe shall be subjected to thermal performance testing in accordance with the test procedures developed in Task 9.5.1. Thermal performance testing consists of test preparation, static, spin, and rewicking tests. Spin testing and rewicking tests shall be performed using the flight test apparatus. However, the static test may be performed without using the flight test apparatus. Heat pipe wall temperatures shall be measured with thermochromic liquid crystal (TLC) coatings, and shall be recorded with a video Cam/Corder as planned for the flight experiment. Maximum power occurs at heat pipe dryout, which shall be defined in two ways for purposes of this experiment:

- Liquid crystal temperature sensors indicate that temperature gradient larger than 10 C exists in the heat pipe evaporator region.
- Thermostat shuts off power when maximum evaporator temperature is reached.

Temperatures corresponding to the various colors of the liquid crystals shall be calibrated using thermocouples. A color standard shall be prepared for viewing through the video Cam/Corder.

5.1.1 Test Preparation: Final assembly of the test apparatus, test setup, and instrumentation of the heat pipes shall be done in accordance with the test procedures prepared in Task 9.5.1. The video camera and DC electric motor for rotating the heat pipe assembly shall be evaluated for low electro-magnetic interference (EMI) prior to starting the thermal performance spin test. Battery life testing will be performed in parallel with the thermal performance tests.

5.1.2 Static Test: The static performance test shall be performed on both FCHPs and VCHPs to determine maximum power without dryout as a function of tilt in 1-g. A fan shall be used to provide forced air cooling for the static testing. Micro-gravity performance shall be estimated by extrapolation of the maximum power data to zero tilt. Each heat pipe shall be subjected to a tilt

test consisting of at least four (4) tilts between 0 and 1.0 in. and temperatures between 40 and 60 C. Heat pipe temperatures shall be maintained within the required range at each power level by variation of the fan speed. Heat pipe wall temperatures shall be measured with TLCs and recorded using the Cam/Corder. Thermocouples shall be attached to the heat pipes to calibrate the TLC performance.

5.1.3 Spin Test: The spin test shall be performed using the flight test apparatus. It shall be performed on both FCHPs and VCHPs with the plane of rotation parallel to the ground. The maximum power of each heat pipe without dryout shall be determined for at least four spin speeds between 0 and 25 rpm. A fan shall be used to augment cooling at low rpm of the test apparatus. Heat pipe temperatures shall be maintained within the required range of 40 to 60 C at each power level by variation of the fan speed. Heat pipe wall temperatures shall be measured with TLCs and recorded using the Cam/Corder.

5.1.4 Rewicking Test: The rewicking test shall be performed on both FCHPs and VCHPs to determine the time required to reprime the wicks or axial grooves after all of the working fluid has been forced to the condenser end of the heat pipe by spinning up to 100 rpm. It shall be performed using the flight test apparatus with the plane of rotation parallel to the ground. The safety shroud fabricated in Task 4.2.6 shall be used while performing this test. After the apparatus has been brought to rest, power will be applied to the evaporator of each heat pipe at various time intervals to determine the time to reprime the wicks. Heat pipe wall temperatures shall be measured with TLCs and recorded using the Cam/Corder.

5.2 Nutation Divergence

Each deliverable heat pipe shall be subjected to nutation divergence ground testing in accordance with the test procedures developed in Task 9.5.1. Nutation divergence testing consists of test preparation, spin, and telemetry tests. These tests shall be performed using the flight test apparatus and instrumentation. However, since it is not possible to test the apparatus as a free flyer in 1-g, it will be mounted onto a special test fixture. Accelerations will be measured with a piezoelectric type accelerometer. The accelerometer signals from LEDs in the Instrument Module (4.2.2) shall be detected and recorded by a photosensitive Receiver/Recorder Module (4.2.3). One recorder channel will be used for data, while a second is used to record commentary using an attached

microphone. Spin speed of the heat pipe assembly will be measured with an optical tachometer.

5.2.1 Test Preparation: Final assembly of the test apparatus, test setup, and instrumentation of the heat pipes shall be done in accordance with the test procedures prepared in Task 9.5.1. A special test fixture will be fabricated to test the nutation divergence assembly. The cordless screwdriver, or equivalent device to be used for spin-up, shall be evaluated for low EMI. Battery life testing will also be performed in parallel with the nutation divergence tests.

5.2.2 Spin Test: In each spin experiment either four (4) FCHPs with two (2) different fill fractions or four (4) VCHPs with two (2) different fill fractions will be assembled in a hoop on the Cruciform Support (4.2.1). The two heat pipes with identical fill fractions shall be mounted diametrically opposed to each other for balance. Tests will be performed to observe the effect of, CG offset, inertia ratio, and spin speed. These results will be used to dynamically balance the apparatus, and verify structural characteristics.

5.2.3 Telemetry Tests: Sufficient tests shall be performed to verify the performance of the telemetry of data from the LEDs in the Instrument Module (4.2.2) to the Receiver/Recorder Module (4.2.3) while spinning. Performance of the optical tachometer shall also be calibrated as part of this test.

5.3 Safety Tests

In addition to electro-magnetic interference (EMI) testing (5.1.1 and 5.2.1), other safety tests will be performed to verify operation of the slip clutch, temperature limiting system, and approved circuit breakers. The safety shroud (4.2.6) will also be tested to verify its capability to prevent physical injury and temperature contact. Results of the ground safety testing will be used to validate the hazard analysis. Any previously unidentified hazards will be added, and any modifications or corrective actions will be made.

WBS 6.0 DELIVER HARDWARE

6.1 Fixed Conductance Heat Pipes (FCHPs)

Twelve (12) FCHPs will be delivered to NASA Johnson Space Center 16 months after effective date of option modification (ADOM). Two (2) sets of four (4) heat pipes will be packed in a middeck drawer for delivery to the NASA Kennedy Space Center for Payload Integration (Task 8.1) into the Shuttle Middeck. The other set of four (4) heat pipes will be used for the KC-135 Flight Testing (Task 7.0) and Crew Training (Task 8.2.2). After completion of the KC-135 Flight Tests and crew training, this set will serve as a spare for the In-Space Experiment.

6.2 Variable Conductance Heat Pipes (VCHPs)

Twelve (12) VCHPs will be delivered to NASA 16 months ADOM. Two (2) sets of four (4) heat pipes will be packed in a middeck drawer for delivery to the NASA Kennedy Space Center for Payload Integration (Task 8.1) into the Shuttle Middeck. The other set of four (4) heat pipes will be used for the KC-135 Flight Testing (Task 7.0) and Crew Training (Task 8.2.2). After completion of the KC-135 Flight Tests and crew training, this set will serve as a spare for the In-Space Experiment.

6.3 Test Apparatus

Two (2) complete sets of experimental apparatus shall be delivered to NASA 16 months ADOM. One (1) set will be packed in middeck drawers for delivery to the NASA Kennedy Space Center for Payload Integration (Task 8.1) into the Shuttle Middeck. The other set will be used for the KC-135 Flight Testing (Task 7.0) and Crew Training (Task 8.2.2). After completion of the KC-135 Flight Tests and crew training, this set will serve as a spare for the In-Space Experiment.

WBS 7.0 KC-135 FLIGHT TESTING

Two (2) KC-135 Flight Tests will be performed to check out operation of the experiment apparatus, verify deployability in a micro-gravity environment, and supplement crew training. Safety aspects of the spinning apparatus will also be verified.

7.1 KC-135 Training

A Class III physical examination is required for four persons plus a backup from NASA JSC. Physiological training for the flight shall be performed at NASA JSC over a period of 1-1/2 days.

7.2 KC-135 Flight Tests

One flight will be for checkout of the apparatus, and another for crew training. KC-135 flight testing shall be performed to engineering level test procedures prepared in Task 9.5.2.

WBS 8.0 IN-SPACE EXPERIMENT

The In-Space Experiment includes Payload Integration into the STS orbiter middeck area, Flight Operations Support, and post flight Data Analysis and Correlation. These tasks will be performed in close co-operation with the NASA Payload Integration Manager (PIM).

8.1 Payload Integration

The Payload Integration Plan (PIP), Interface Control Document (ICD), all Annexes to the PIP, and other supporting documentation for the flight experiment shall be baselined. Baselined means signed by both NSTS and Hughes. These documents are initiated and controlled by the Payload Integration Manager at NASA JSC. Hughes will work closely with the Payload Integration Manager on system electrical power, thermal, and weight requirements. Formal procedures for the In-Space experiment shall be prepared using the Final Report from Phase B as a guideline. Two trips to NASA JSC will be required to support the preparation of these documents.

8.2 Flight Operations Support

Flight Operations Support includes Flight Readiness, Crew Training, and Flight Support. These tasks are described in the following sections.

8.2.1 Flight Readiness: The documentation baselined in Payload Integration above (Task 8.1) will be updated and finalized. Hughes will provide instructions for stowing the heat pipes and test apparatus in the STS orbiter middeck locker drawers for Shuttle launch and re-entry. Instructions will be provided for deployment of the test apparatus once in orbit. Hughes will work closely with the Payload Integration Manager to accommodate any launch window opportunities or changes in launch dates.

8.2.2 Crew Training: Hughes personnel assigned to the IN-STEP program shall take part in crew training. This training will be performed both at the NASA Johnson Space Center in Houston, Texas and at the Hughes Aircraft Company facilities in Torrance, California. Crew training will make extensive use of the Middeck mockup facility located at the Johnson Space Center and will include a flight on NASA's KC-135 free-fall training aircraft (Task 7.0).

8.2.3 Launch Readiness Date: This is a milestone on the schedule which represents the point in time when all documentation, experimental hardware, crew training, and safety requirements are completed. It is the earliest possible date to launch.

8.2.4 Flight Support

The test procedures developed in Tasks 8.1 and 8.2 will be used by specially trained STS Orbiter crew members to perform In-Space thermal performance and nutation divergence heat pipe experiments. Hughes personnel will support flight operations through real time voice and video downlinks.

8.3 Data analysis and Correlation

After return of the STS Orbiter, Hughes personnel will be de-briefed by the crew members. This de-briefing will take place at NASA JSC. The test results will be analyzed and correlated with the ground test data from Task 5.0 and the analytical models generated in Task 2.1.

WBS 9.0 DOCUMENTATION

9.1 Technical Requirements:

The Technical Requirements Document is a list of the experiment requirements such as weight, power, battery usage, stowage, and deployment envelopes. It will be generated early in Phase C/D by Hughes, working with the NASA Payload Integration Manager. It will serve as a checklist to prevent overlooking any of the key experimental requirements later in the program. The GSFC project manager must approve the Technical Requirements Document before detail design is started.

9.2 Quality Assurance Plan:

A formal Quality Assurance Plan will be prepared by Hughes Quality Assurance Engineering and submitted to NASA for review. The plan will be in compliance with MIL-Q-9858A quality requirements. Since the experiment components are packed in foam in middeck drawers for launch and re-entry, no environmental qualification tests (e. g., vibration, shock) are envisioned. The video camera will be qualified by similarity.

9.3 Monthly Progress Reports

Progress reports shall include brief descriptions of: 1) contract status, 2) all work accomplished during each month of contract performance, and 3) any technical problems encountered during the reporting period and proposed solutions. In addition, the report shall provide cumulative vs. planned

expenditures and schedules with a brief discussion of significant costs, schedule deviations, and the proposed corrective action. Reports shall be in narrative form, brief, and informal in content.

9.4 Data Packages

A data package shall be submitted to NASA at least ten (10) days prior to any Design Review or Presentation, except for Flight De-Briefing which will be submitted five (5) days prior to the de-briefing. The data package shall contain sufficient material for the GSFC project manager to prepare for the subject Review or Presentation.

9.4.1 Critical Design Review Data Package: The Critical Design Review Data Package shall include the Technical Requirements Document, Quality Assurance Plan, results of the Detail Design including mechanical, electrical, and thermal analyses, safety evaluation, and the drawing package.

9.4.2 Acceptance Review Data Package: The Acceptance Review Data Package shall include the Phase 0-I and II Safety Reports, baselined Flight Support Documents including the Payload Integration Plan (PIP), Interface Control Document (ICD), and PIP Annexes, results of the Ground Testing, and KC-135 Flight Test Procedures.

9.4.3 Flight Operations Data Package: The Flight Operations Data Package shall include finalized copies of all Flight Support Documentation and the Phase III Safety Report.

9.4.4 Flight De-Briefing: The Flight De-Briefing Data Package will consist of a list of questions for the STS orbiter crew concerning the In-Space experiment. These questions must be submitted to NASA five (5) days prior to the de-briefing.

9.4.5 Post Flight Review: The Post Flight Review Data Package shall contain the results of the In-Space experiment data analysis and correlation, Final Report and video tapes of the In-Space Experiment.

9.5 Test Procedures

Written test procedures shall be prepared for Ground Testing and the KC-135 Flight Test. These test procedures shall be submitted to the NASA Technical Officer for review within two (2) weeks prior to start of the test. They are in addition to the formal In-Space experiment procedures which are included under Payload Integration (Task 8.1) and Flight Readiness (Task 8.2.1).

9.5.1 Ground Test Procedures: Ground test procedures shall be prepared and submitted to NASA for review within 6 months ADOM. The procedures shall include descriptions of the test setup and instrumentation for thermal performance, nutation divergence, and safety testing. Thermal performance will include static, spin, and rewicking tests as outlined in WBS 5.0 of this Statement of Work. Nutation Divergence testing shall include spin, and telemetry tests, which are also outlined in WBS 5.0 of this Statement of Work.

9.5.2 KC-135 Procedures: Engineering Level test procedures will be prepared for the KC-135 Flight Testing. The purpose of this test is outlined in WBS 7.0 of this Statement of Work. These procedures will be submitted to NASA 13 months ADOM.

9.6 Flight Support Documents

The Payload Integration Plan (PIP), Interface Control Document (ICD), and all PIP Annexes are prepared as part of Payload Integration (Task 8.1) and Flight Readiness (Task 8.2.1). They are initiated and controlled by the NASA Payload Integration Manager. However, these documents must be signed by NSTS and Hughes prior to launch go-ahead.

9.7 Interim Report

An interim written report shall be prepared to document the detail design analysis, fabrication, and ground test results. The draft report will be submitted to NASA 13 months ADOM. The final version of the Interim Report shall be delivered one month after the draft is returned from NASA review.

9.8 Safety Report

Three Safety Reports will be required for this program: Phase 0-I, Phase II, and Phase III. The Phase III Safety Report will include the results of the ground safety testing for the components unique to this Middeck experiment. Safety reports shall be submitted 75 days before any safety review at NASA. The Phase III Safety Report must be approved by NASA prior to go-ahead for the In-Space Experiment.

9.9 Final Report

The final written report will be prepared to document the Phase C/D investigation, including any significant results produced by the investigation. The report will summarize the results of the In-Space Experiment, and will provide information useful to the aerospace community. The draft report will be submitted for NASA review 28 months ADOM. The final version of the Final Report will be delivered one month after the draft is returned from NASA review.

WBS 10.0 REVIEWS AND MEETINGS

10.1 Critical Design Review

A critical design review will be scheduled during the fifth month ADOM at NASA GSFC. The detail design of heat pipes and experiment apparatus, mechanical, electrical, and thermal analyses, safety evaluation, and the drawing package will be presented for NASA review. Fabrication of the experiment hardware will not start until the documentation presented at this review is approved by NASA.

10.2 Documentation Support

Two (2) meetings are planned during the Payload Integration Task (8.1) to work on Flight Support Documentation with the Payload Integration Manager at NASA JSC.

10.3 Safety Reviews

Three (3) safety reviews are scheduled at NASA JSC: Phase 0-I, Phase II, and Phase III. The flight readiness task cannot begin until approval of the Phase II Safety Review. Launch will be contingent on the Phase III Safety approval.

10.4 Acceptance Review

An Acceptance Review will be scheduled at Hughes after completion of the Ground Testing (Task 5.0). The Acceptance Review will include presentation of the baselined flight support documentation, hardware inspection records, results of the ground testing, safety evaluations, and the KC-135 flight test procedures. The technical preparedness of the experiment will be reviewed as well as the project plan including cost and schedule. The test hardware will be delivered after NASA approval of the Acceptance Review.

10.5 Crew Training

Crew training will start after delivery of the experimental hardware to NASA JSC. Training will consist of three (3) two-day sessions at NASA JSC. A crew familiarization meeting will be held first to review the background and purpose of the experiment with the crew, followed by two other hands-on training sessions. Crew members may visit the Hughes facility at any time before or after delivery of the hardware.

10.6 Flight Operations Review

The Flight Operations Review will be held within one (1) month prior to launch of the In-Space Experiment. It will serve as a briefing on the flight experiment for the crew members. Finalized Payload Integration and other Flight Support Documentation will be reviewed at this time.

10.7 Flight De-Briefing

This is a question and answer period to be held at NASA JSC with the crew members one (1) week after landing of the STS Orbiter. All questions must be submitted in writing five (5) days prior to the de-briefing.

10.8 Post Flight Review

Results of the flight data analysis and correlation, along with any significant findings, will be presented in a formal review at NASA GSFC. This review will take place within approximately three (3) months following the flight experiment.

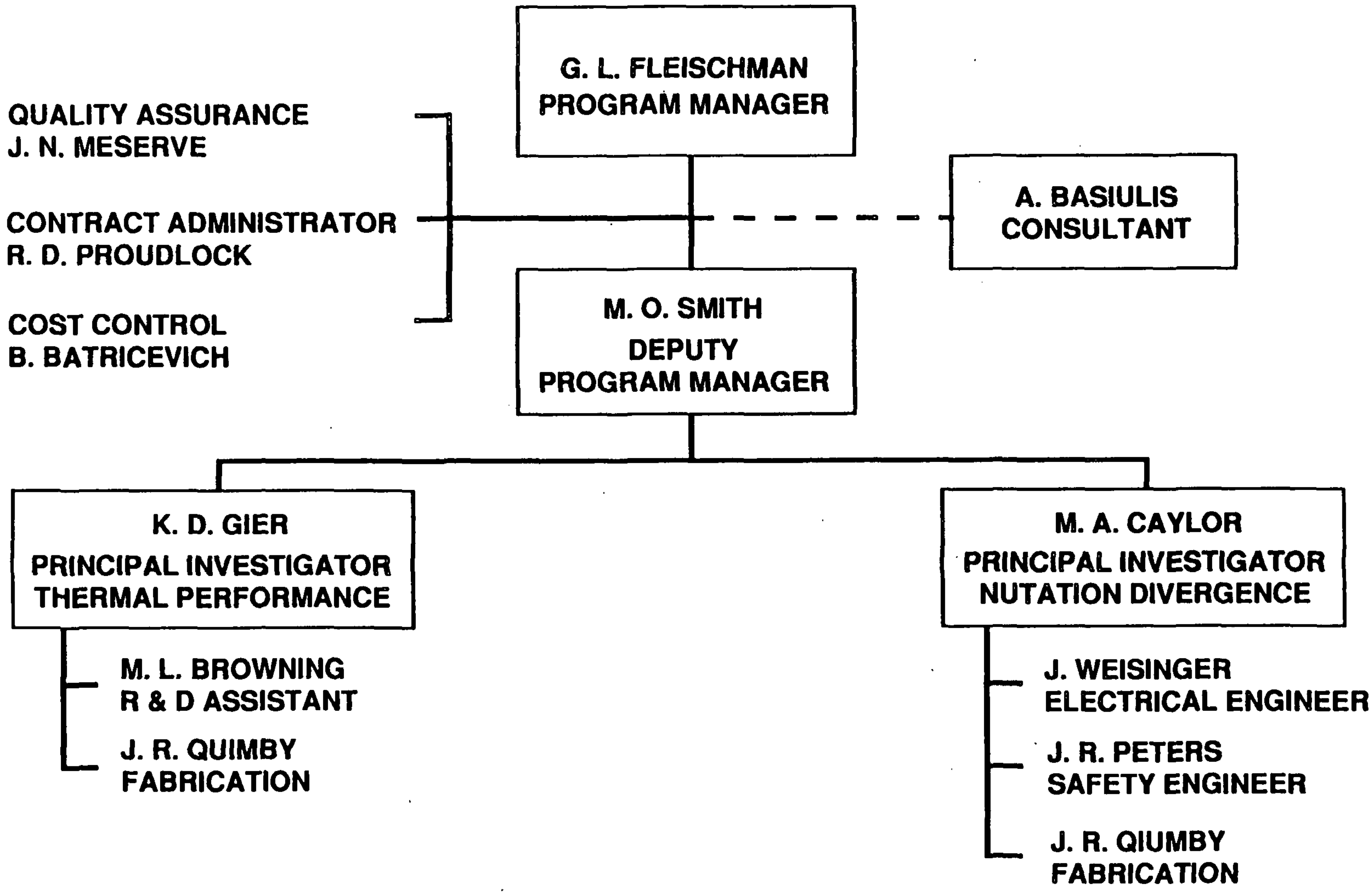
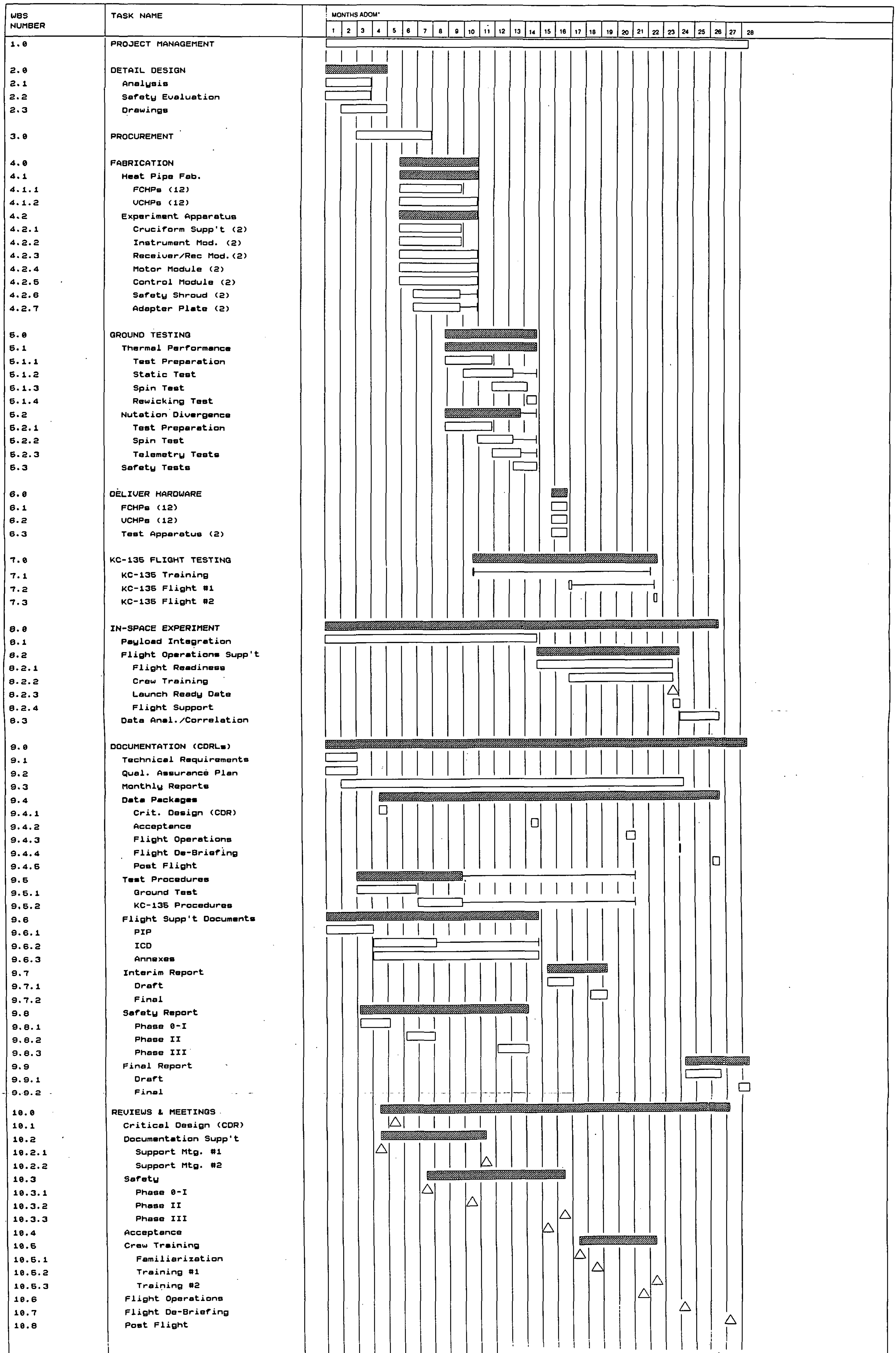


Figure A-1 Program organization for in-space heat pipe (HPP) experiment phase C/D.

FOLDOUT FRAME 1.



Industry & University In-Space Technology Experiments

Figure A-2
Heat Pipe Performance (HPP) Experiment
Phase C/D: Experiment Design, Fabrication, and Test.

AS OF DATE 22DEC89 TIME LINE R GRAPHICS

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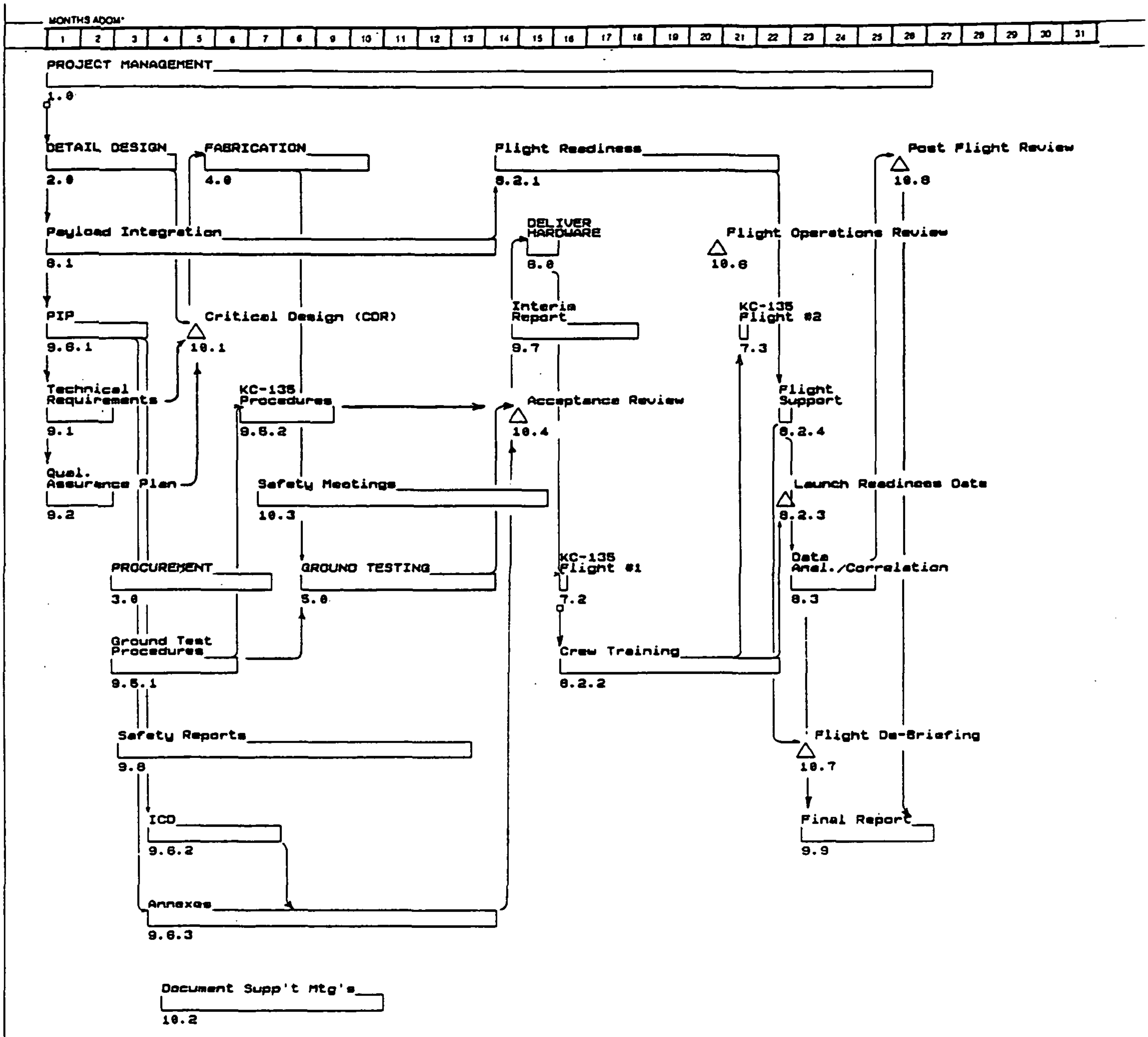
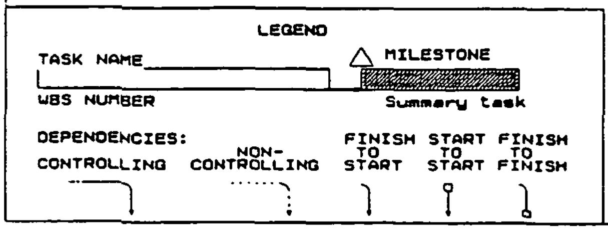
C-2.



* AFTER EFFECTIVE DATE OF OPTION MODIFICATION



Industry & University In-Space Technology Experiments

Figure A-3
Heat Pipe Performance (HPP) Experiment

Phase C/D: Experiment Design, Fabrication, and Test.

AS OF DATE 22DEC89 | TIME LINE R GRAPHICS

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HUGHES
HUGHES AIRCRAFT COMPANY

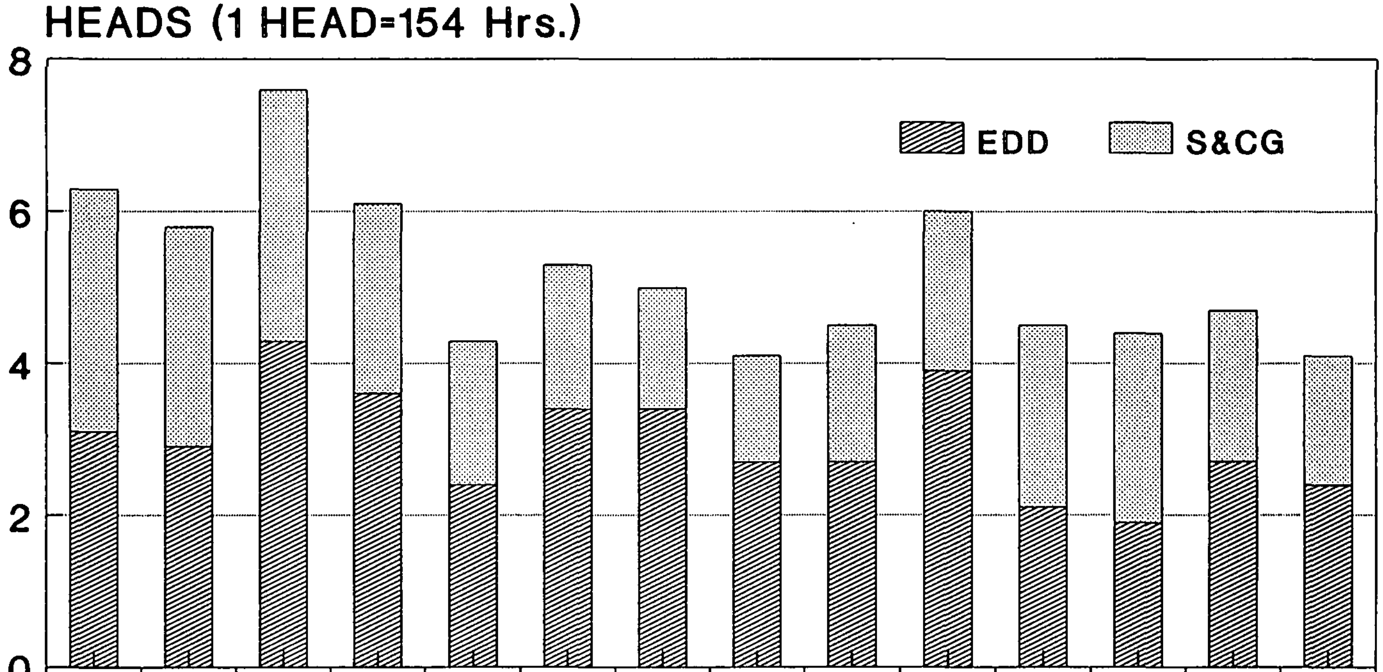
ELECTRON DYNAMICS DIVISION

MATERIAL - FOR PHASE C/D INVESTIGATION OF MICRO-GRAVITY

08-Oct-89

PART NUMBER	DESCRIPTION	QTY	UNIT	TOTAL	BASIS	DATE	SOURCE
HK5165R261112B	ELECTRICAL WARMER	50	14.75	737.50	WRITTEN QUOTE	8-22-89	PENFAGON FOR MINCO
3500YT120/B210/0	THERMOSTAT	50	41.83	2,091.50	WRITTEN QUOTE	8-22-89	ELMWOOD
(STD TEMP)	LIQUID CRYSTAL TEMP. DISP	20	20.00	400.00	WRITTEN QUOTE	8-22-89	HALLCREST
(ABOVE 40 C)	LIQUID CRYSTAL TEMP. DISP	20	60.00	1,200.00	WRITTEN QUOTE	8-22-89	HALLCREST
(BELOW 40 C)	LIQUID CRYSTAL TEMP. DISP	20	50.00	1,000.00	WRITTEN QUOTE	8-22-89	HALLCREST
	CRUCIFORM (MAT'L ONLY)	1	305.28	305.28	WRITTEN QUOTE	8-28-89	LEED PLASTICS
	DC MOTOR GEARHEAD ASSY	4	335.20	1,340.80	WRITTEN QUOTE	8-23-89	MICRO NO
BLD403	SERVO AMPLIFIER	4	266.90	1,067.60	WRITTEN QUOTE	8-23-89	MICRO NO
SAS-16	OVERLOAD CLUTCH	3	28.65	85.95	CATALOG	9/28/89	POLYCLUTCH
	MOD'S FOR NON-STD SHAFTS	3	6.00	18.00	PHONE QUOTE	9/28/89	POLYCLUTCH
03121609 00	MOTOR HOUSING	3	21.37	64.11	WRITTEN QUOTE	8-25-89	ROSE ENCLOSURES
03121211 00	CONTROL HOUSING	3	20.46	61.38	WRITTEN QUOTE	8-25-89	ROSE ENCLOSURES
DAY-490-10	SLIP RING ASSY	3	2,765.00	8,295.00	WRITTEN QUOTE	8-18-89	AIRFLYTE
eEA5-AA-5SP	WARMER SELECTOR SWITCH	4	45.33	181.32	WRITTEN QUOTE	8-23-89	JANCO
EA45-AA-3SP	DISPLAY SELECTOR SWITCH	4	45.33	181.32	WRITTEN QUOTE	8-23-89	JANCO
D45BA-2ALCSP	MOTOR SPEED CONTROL	4	48.36	193.44	WRITTEN QUOTE	8-23-89	JANCO
CMN6710	LED NUMERIC DISPLAY	20	3.74	74.80	WRITTEN QUOTE	8-23-89	ELECTRIC SWITCHES
46426-81	WARMER TIMER	4	25.65	102.60	WRITTEN QUOTE	8-23-89	ELECTRIC SWITCHES
44-100-P10	CIRCUIT BREAKER	4	7.70	30.80	WRITTEN QUOTE	8-23-89	ELECTRIC SWITCHES
	INSTRUMENT HSG (MAT'L)	8	10.49	83.92	WRITTEN QUOTE	8-29-89	LEED PLASTICS
SUBTOTAL				17,515.32			
	TELEMETRY SYSTEM	2		27,000.00	WRITTEN QUOTE	9-08-89	APPLIED DYN. LAB
R-8204-00	DIGITAL TACHOMETER	4	190.00	760.00	CATALOG	1986	COLE-WARNER
	SONY CAM/CORDER	2	2,000.00	4,000.00	STORE ITEM	9-05-89	M. SMITH
	VIDEO LIGHT	2	200.00	400.00	STORE ITEM	9-05-89	M. SMITH
SUBTOTAL				32,160.00			
DB735641	CHP GROOVE MACHINING	16	975.00	15,600.00	WRITTEN QUOTE	8-29 89	WIRE CUT CO.
	MODEL TUBING	50	12.94 ft	647.00	PHONE QUOTE	9-28-89	TUBESALES
	END CAP CLEANING	36	6.25	225.00	PO 9943550	12/18/86	HIGHLAND
	RESERVOIR, UPPER HEMI.	12	161.00	1,932.00	PO 920289	04-22-86	WOODRUFF
	RESEVOIR, UPPER HEMI ASSY	9	100.00	900.00	PO 933604	07/18/86	G. FLEISCHMAN
	WELDING SHOP AID	1	250.00	250.00	PO 933604	07/18/86	EBW
	SET-UP CHARGE	1	100.00	100.00	PO 933604	07/18/86	EBW
	CERTIFICATION OF	1	200.00	200.00	PO 933604	07/18/86	EBW
	END CAP	36	5.25	189.00	PO 929306	05/02/86	MICROMETIRC
	RESERVOIR, BODY	12	87.00	1,044.00	PO 920288	04/22/86	WOODRUFF
	RESERVOIRLOWER HEMI.	12	187.00	2,244.00	PO 920289	07/08/86	WOODRUFF
	RESERVOIR, LOWER HEMI. ASSY	9	200.00	1,800.00	PO 931654	07/08/86	EBW
	SET-UP CHARGE	1	100.00	100.00	PO 931654	07/08/86	EBW
	CERTIFICATION	1	200.00	200.00	PO 931654	07/08/86	EBW
	WELDING AIDS	1	250.00	250.00	PO 931654	07/08/86	EBW
	TUBE-TO-LWR HEMI ASSY	9	125.00	1,125.00	PO 931593	07/14/86	EBW
	WELDING AIDS	1	250.00	250.00	PO 931593	07/14/86	EBW
	SET-UP CHARGE	1	100.00	100.00	PO 931593	07/14/86	EBW
	ENG. DEV. & CERTS	1	200.00	200.00	PO 931593	07/14/86	EBW
	RESERVOIR PLUG	12	67.00	804.00	PO 920289	09/20/86	WOODRUFF
	WICK MATERIAL	24	4.63 ft	111.12	PO 921821	02/26/86	METEX
	MACHINED EXTRUSION	9	70.00	630.00	PO 920278	04/08/86	DEL AMO MFG
	MACHINED EXTRUSION CLEANING	9	27.50	247.50	PO 931542	06/13/86	HIGHLAND
SUBTOTAL				29,148.62			
GRAND TOTAL				78,823.94			

HEAT PIPE PERFORMANCE EXPERIMENT
LABOR REQUIREMENTS BY MONTH

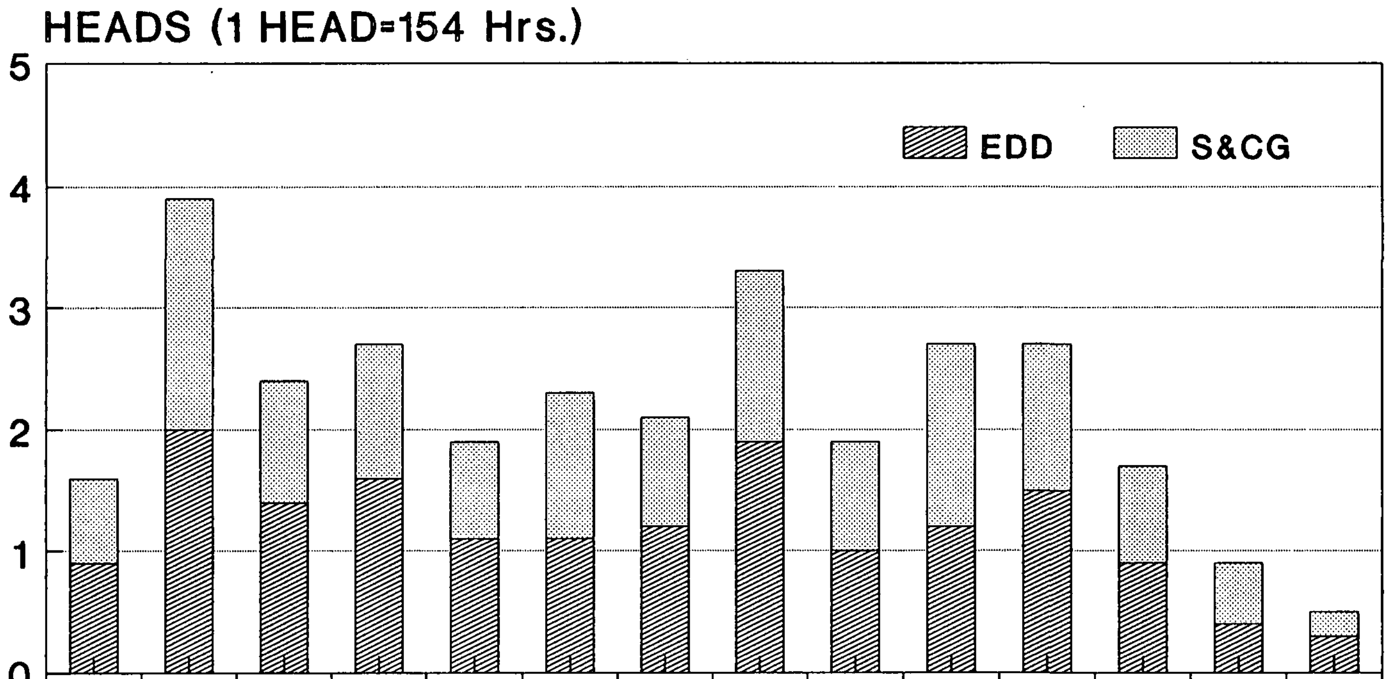


	1	2	3	4	5	6	7	8	9	10	11	12	13	14
S&CG	3.2	2.9	3.3	2.5	1.9	1.9	1.6	1.4	1.8	2.1	2.4	2.5	2	1.7
EDD	3.1	2.9	4.3	3.6	2.4	3.4	3.4	2.7	2.7	3.9	2.1	1.9	2.7	2.4

MONTHS ADOM*

* After Effective Date of Option Modification

HEAT PIPE PERFORMANCE EXPERIMENT
LABOR REQUIREMENTS BY MONTH

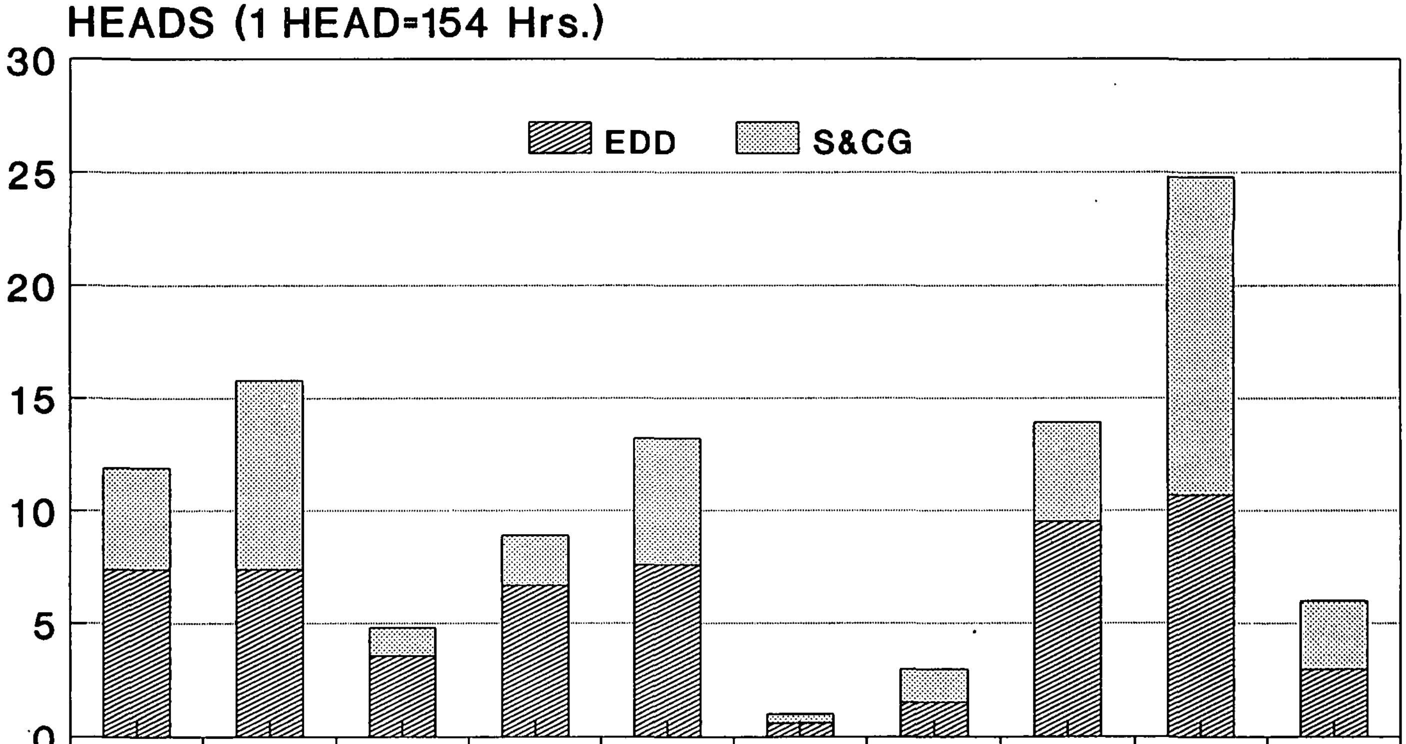


	15	16	17	18	19	20	21	22	23	24	25	26	27	28
S&CG	0.7	1.9	1	1.1	0.8	1.2	0.9	1.4	0.9	1.5	1.2	0.8	0.5	0.2
EDD	0.9	2	1.4	1.6	1.1	1.1	1.2	1.9	1	1.2	1.5	0.9	0.4	0.3

MONTHS ADOM*

* After Effective Date of
Option Modification

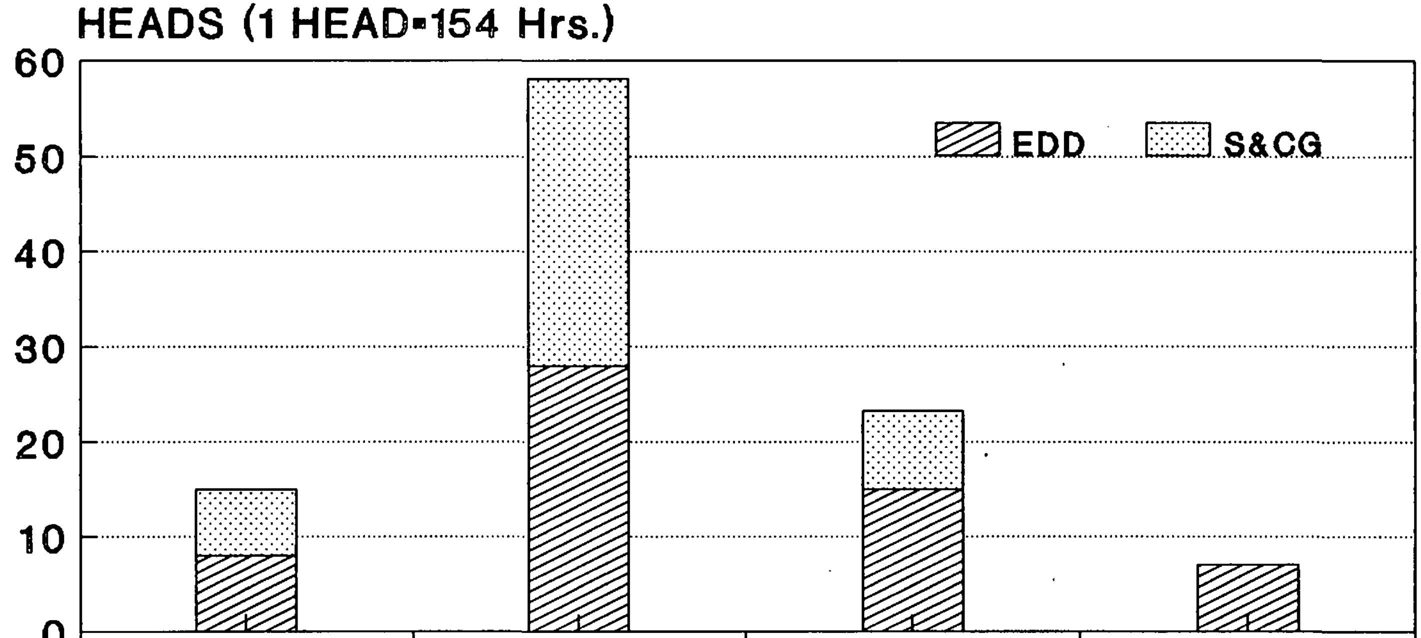
HEAT PIPE PERFORMANCE EXPERIMENT
LABOR REQUIREMENTS BY WBS ELEMENT



	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
S&CG	4.5	8.4	1.2	2.2	5.6	0.4	1.5	4.4	14.1	3
EDD	7.4	7.4	3.6	6.7	7.6	0.6	1.5	9.5	10.7	3

WBS ELEMENT

HEAT PIPE PERFORMANCE EXPERIMENT
LABOR REQUIREMENTS BY CATEGORY



	SMTS	MTS	TE	GE
S&CG	7	30	8.3	0
EDD	8	28	15	7

LABOR CATEGORY*

* SMTS = Senior Member Tech. Staff
MTS = Member Tech. Staff
TE = Technical Eng'r; GE = General Eng'r